Modelling freshwater resources use and the economic impacts of demand-driven water scarcity

Victor-Alexandru Nechifor-Voştinaru

UCL Institute for Sustainable Resources

University College London

A thesis submitted for the degree of

Doctor of Philosophy

Declaration

I, Victor-Alexandru Nechifor-Voştinaru confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Victor-Alexandru Nechifor-Voştinaru

Publications

Publications based on this thesis

Peer-reviewed publications

Nechifor, V. & Winning, M., 2017. Projecting irrigation water requirements across multiple socio-economic development futures – A global CGE assessment. *Water Resources and Economics*, 20, pp.16–30.

Conferences

Nechifor, V., 2018. Global economic and food security impacts of demand-driven water scarcity. IAERE 2018, Turin, Italy.

Nechifor, V., 2017. Energy mix data for global economic analyses of water scarcity impacts. *ETSAP workshop on modelling the water-energy nexus*, Zurich, Switzerland.

Nechifor, V. & Winning, M., 2017. Higher CO2 concentrations impacts over global crop production and irrigation water requirements. *GTAP Conference 2017*, West Lafayette, USA.

Nechifor, V. & Winning, M., 2016. Irrigation freshwater withdrawal stress in future climate and socio-economic scenarios. *EcoMod Conference 2016*, Lisbon, Portugal.

Other peer-reviewed publications

Bleischwitz, R., Nechifor, V., Winning, M., Huang, B., Geng, Y., 2018. Extrapolation or saturation– an exploration into growth patterns, development stages and decoupling. *Global Environmental Change*, 48, pp.86–96.

Winning, M., Calzadilla, A., Bleischwitz, R., Nechifor, V., 2017. Towards a circular economy: insights based on the development of the global ENGAGE-materials model and evidence for the iron and steel industry. *International Economics and Economic Policy*, 14(3), pp.383–407.

Acknowledgements

I would first like to thank my supervisors, Prof. Paul Ekins and Dr. Matthew Winning for their continuous support and inspiration. Without doubt, Paul's work on the Sustainability Gap represented an important determinant in my decision to plunge into the field of economy-wide modelling of resource use. At the same time, I am grateful for Matthew's generous availability to discuss the numerous questions and dilemmas I have been confronting throughout my PhD.

Equally, I would want to thank my examiners, Dr. Rob Dellink and Dr. Dirk Willenbockel, for taking the time to analyse my work and to discuss its content during the viva. Their valuable feedback has highlighted some of my blind spots and have helped improve the quality of the thesis.

I would also want to extend a special thanks to Dr. Alvaro Calzadilla and Prof. Raimund Bleischwitz for their involvement and interest in my research. The many interactions with Alvaro on water and resource modelling using the CGE framework have been both intellectually stimulating and a source of confidence.

The time I spent at the institute was far from being a solitary journey thanks to the great environment I was part of. I am grateful for all exchanges I had over the years with the many brilliant PhD students here, Stijn van Ewijk, Simon Damkjaer, Louise Guibrunet, Darshini Ravindranath, Arkaitz Usubiaga and Adam Roer in particular. I would also like to show my appreciation to Alison Parker, Mae Oroszlany and Rosanna Seels from the administration team for all their amazing support.

I would equally want to thank people outside the institute who have contributed to the research development with model data and essential guidance in this regard – Dr. Stefan Siebert, Dr. Martina Flörke and Dr. Jacob Schewe.

Last but not least, I would like to express my gratitude to my mother Aida, my sister Irina and to my dear friends Andreea, Flavius, Radu and Liviu for their care and encouragements during these years.

Abstract

Water deficits are increasingly perceived as a threat to future global prosperity. Given current projections of population growth and economic development, the pressure over the water resource base coming from human abstraction would continue to expand including in regions currently dealing with water scarcity. The aim of this thesis is to determine the implications of demand-driven water deficits for economic development and food security by accounting for three major factors influencing future water demand – income, population and climate change. The first main contribution of this thesis consists in the advance of the current state-of-the-art in the macroeconomic modelling of freshwater use and the endogenous mechanisms of adaptation to water scarcity. The second contribution is the development of knowledge regarding the sector-specific impacts of water scarcity under different water allocation regimes. The analyses are carried out through a global Computable General Equilibrium model (RESCU-Water) which considers the heterogeneity of water uses across the economy. Due to the importance of irrigation in global withdrawals, an emphasis is made on crop systems through a bottom-up representation of irrigated and rainfed crop production. The findings show that the aggregate economic effects of water scarcity highly depend on the choice of the water allocation method, with important trade-offs between food security and GDP impacts. Next, although the demand for irrigation water is slowing down in the next decades, any water allocation regime based on differences in sectoral water productivities will have a significant impact on crop production notably on staple crops. In this context, the demand-driven water deficits become an additional constraint for crop systems and further amplify the negative effects of climate change on crop output.

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Chapter 1. Introduction

1.1. Background

Freshwater is essential to supporting life on the planet by providing a wide range of ecosystem services across all relevant dimensions – regulation, resource provision, cultural and supporting (Aylward et al. 2005). From a resource provision angle, the availability of freshwater is crucial to sustaining human food requirements at current population levels as more than two-fifths of world crop production now come from irrigated land. Other human needs are dependent on freshwater and are increasingly competing for access to resources in water-scarce regions – household use for sanitation and drinking, cooling of thermal power plants, industrial uses in mining, construction or manufacturing.

Although water covers more than two-thirds of the Earth's surface leading thus to a perception of abundance, freshwater stocks represent only 2.5% of all resources (Shiklomanov 1993), whilst the renewable freshwater component accounts for a much smaller share. Furthermore, the renewable freshwater availability is unevenly distributed across world regions with a result that a great proportion of the global population lives in conditions of water stress (1.2 billion people currently - UNESCO 2015). At the same time, human freshwater abstraction from the natural environment has expanded substantially during the 20th century mainly driven by irrigation requirements, with freshwater demand for crop production currently representing 70% of all withdrawals. However, industrialised regions have increased their freshwater demand outside agriculture due to the development of water-intensive industries and to urbanisation.

Global withdrawals currently represent about 10% of total renewable freshwater resources, a figure that hides the fact that large geographical areas are now dealing with persistent water demand-supply imbalances. Many aquifers are now overexploited and the human appropriation of freshwater has already been manifested through alterations of run-off profiles in major river basins (Postel et al. 1996). Groundwater pumping has led to a continuous lowering of water tables (Wada et al. 2010) as water abstractions exceed the recharge rates of aquifers. For the temporal balancing of demand and supply, man-made freshwater storage capacity is estimated to amount to 8000 km^3 (Biemans et al. 2011) or twice the global withdrawals. However, in some areas, total mean annual supply is simply not enough to meet total demand. Hence, the geographical balancing at different scales, from local to macro-regional, can be resolved either through costly water transfer schemes or through the trade of 'virtual water' i.e. water embedded in traded products.

Many regions around the world are currently using unsustainable levels of freshwater. Still, there are very few examples where water scarcity is acknowledged through explicit withdrawal restrictions and through an allocation mechanism to enable the optimisation of water productivity (mainly occurring in developed regions e.g. Murray-Darling Basin in Australia). In general, freshwater is improperly priced (Bosworth & Perry 2004) by not considering any scarcity value in areas where demand exceeds sustainable supply, and with direct subsidies for water uses (charging for water uses below the operation and maintenance supply costs) or indirect subsidies (e.g. energy subsidies in groundwater pumping) further distorting the potential for a judicious use of the finite resource base.

1.2. Motivation of this thesis

There is a growing concern that further population and economic growth will lead to a significant increase in freshwater demand with potentially large-scale disruptions of economic activities. Demand growth is expected notably in developing or emerging economies, some of which are already confronted with unsustainable water withdrawals (Southern Asia, China, Middle East and Northern Africa). As the economies in these regions continue to grow and diversify, a significant expansion in freshwater use will come from industrial sectors and households, in addition to irrigated crop production. Water demand is thus expected to grow fourfold globally for manufacturing and to more than double for thermal power plants and municipal uses (Marchal et al. 2011).

Climate change will be a further complicating factor for understanding freshwater demand patterns as this will impact crop growing conditions (yields, evapotranspiration rates and natural soil moisture) and will implicitly alter irrigation water demand. The combined effects of water scarcity, climate change and other environmental damages (e.g. soil erosion) are estimated to result in a 25% drop in world food production by the end of this century (Nellemann 2009). Also, climate change would alter the operating environment of other productive sectors (e.g. by inducing higher evaporation rates of cooling water in power plants). Therefore, given the current inertia of humanity in stopping the increases in atmospheric greenhouse gases (GHGs) concentrations, assessments of future freshwater demand need to incorporate scenarios of changes in climatic conditions for the different likely concentration pathways.

The topic of sustainability of freshwater use and its relationship to the well-being and even to the survival of many people have been on the public policy agenda for some time. It was in the Dublin Conference in 1992 that the recognition of freshwater water as a “finite and vulnerable resource” (Principle 1) was made on a global scale. At the same time, the importance of economic activities in the management of freshwater resources was emphasised through the acknowledgement of the dual dimension of freshwater as a basic human right but also as an economic good (Principle 5). It was also the Dublin Conference which enabled the creation of the World Water Council, an international body aiming to "build political commitment and trigger action on critical water issues at all levels, including the highest decision-making level, to facilitate the efficient conservation, protection, development, planning, management and use of water in all its dimensions on an environmentally sustainable basis for the benefit of all life on earth".

Currently, there is a growing number of expert- and policy-maker platforms such as the World Water Forum, the International Network of Basin Organizations or the World Water Week in Stockholm, focusing on water management issues from a local to a global level. Furthermore, the 2030 Water Resources Group through its private-public-civic society collaboration aims at solving the mismatches between demand and supply of freshwater by 2030. In the recent Sustainable Development Goals (SDG) framework, water is introduced as a major topic through a standalone goal (Goal 6). This SDG is emphasising the human rights dimension of access to drinking water, sanitation and hygiene (WASH) in line with the previous Millennium Development Goals (Target 7.C). Alongside, the aim of sustainable freshwater use is set through sub-goal 6.4. Thus, by 2030, it is set "[to] substantially increase water-use efficiency across all sectors and [to] ensure sustainable withdrawals and supply of freshwater to address water scarcity, and [to] substantially reduce the number of people suffering from water scarcity".

An expanding body of academic work has focused on the topic of future demand-driven water scarcity coming from socioeconomic development and climate change. This was facilitated by the methodological improvements in water demand estimations and data collection. Due to the distributed nature of water withdrawals, quantitative evaluations of freshwater uses are determined indirectly through estimation efforts, notably when assessed at a larger scale such as a country or the globe. More detailed national statistics combined with remote sensing data of crop growth and groundwater depletion have enabled a better understanding of evapotranspiration patterns and irrigation water uses. Furthermore, water life-cycle analyses for different industrial activities have allowed for a more detailed quantification of water inputs in sectors outside agriculture. Thus, such estimations in conjunction with projections of demand levels coming from economic and population growth have revealed a water "supply gap" which, by 2030, could be in the order of 2000km^3 (McKinsey 2009) representing a third of the estimated total demand at that point.

In spite of the multi-sectoral uses of water and the relevance of water to the global economy (1.4 billion jobs dependent on water availability - UNESCO 2016), most analyses have not included the economy-wide impacts of such water deficits. In the past decade, assessments using economic modelling have largely focused on the incidence of water scarcity on crop production. The feedback effect of freshwater scarcity on economic activity and continued growth in prosperity has been addressed only to a limited extent in the existing literature. Therefore, a better understanding of the constraints imposed by bounded freshwater supply on economic growth is necessary in order to assess the centrality of this natural resource to continued socioeconomic development. Only recently, the topic of the macroeconomic impacts of demand-driven water deficits has gained attention through the World Bank (2016) report. Nevertheless, the modelling framework used in the analysis does not include an adequate level of sectoral detail regarding freshwater uses.

At the same time, the implications of climate change over water scarcity have mostly been analysed from a water supply perspective by exploring the changes in hydrological cycles. Thus, alterations to precipitation patterns could result in a deepening of scarcity conditions for a large share of the global population (Schewe et al. 2014). However, changes in scarcity levels in a global setting stemming from the modifications of climate change to water productivities and water demand patterns have been less explored.

With freshwater being used as an input to a vast number of economic activities, an economy-wide analysis of water scarcity impacts would have the following pre-requisites:

(1) A representation of freshwater demand detailed by user type under different pathways for socioeconomic and climate change scenarios.
(2) The possibility to allocate freshwater across users using both market and non-market based methods. Market-based methods would need to take into account the differences in water productivity across water users.
(3) The ability to measure the impacts at a macroeconomic level (GDP) and at a sector-specific level (output).

As production of water-intensive commodities, notably crops, is increasingly influenced at a local level by global demand, the inclusion of international trade flows would represent an additional pre-requisite (4) to the above. The trade of “virtual water”, the water embedded in traded products, has doubled in the 1986-2007 time span reaching 567km^3 (Dalin et al. 2012). Because of the growing trade volumes occurring also between water-challenged countries (e.g. flows between India and Pakistan), water scarcity in one region should not be treated in isolation to that in other regions. Thus, the 2012 World Water Development Report (UNESCO 2012) underlines that freshwater cannot be considered "solely a local, national or regional issue that can be governed at any of those levels alone […] global interdependencies are woven through water, and decisions relating to water use on a local, national or regional level often cannot be isolated from global drivers, trends and uncertainties". Therefore, these large-scale implications of demand and supply interactions which often go beyond national boundaries make the case for a global-level analysis.

1.3. Aim, research questions and scope

The aim of this thesis is to determine the economy-wide impacts of water scarcity induced by future changes in freshwater demand. This is done by including the four pre-requisites introduced above into a global economy-wide model which was purposely built for this type of analysis. Freshwater is thus treated as a distinct factor of production, its demand is differentiated by economic activity and a re-allocation between users in conditions of water scarcity becomes possible using alternative water management options. The model employed (RESCU-Water) is built using a Computable General Equilibrium (CGE) framework and is structured around 20 world regions and 31 economic activities. The motivation of using this method is determined by its inherent capacity to represent the global economy through production technologies for a large number of sectors and regions.

As opposed to Input-Output models which also comprise a multi-sectoral description of an economy using national accounts, CGE models incorporate the substitution effects between factors and commodities that stem from relative price changes as market conditions are altered. Therefore, the dynamics in the use of freshwater by economic activities are put in relation to the availability of other factors of production. This enables the RESCU-Water model to be consistent across economic activities when analysing the relationship between socioeconomic development and freshwater demand. At the same time, using a sectoral representation of water uses, the model allows for an advanced specification of adaptation mechanisms to water shortages using market price signals.

The implementation of scenarios measuring the impacts of future water scarcity is reliant on projections of freshwater use. The model builds on previous research done in integrated assessments related to water use projections for industrial and municipal water users. Withdrawals for thermal power production are also treated distinctly by considering the evolution of the production technological mix derived from global energy systems modelling (TIAM-UCL). At the same time, given the importance of irrigated crops to global withdrawals, the applications of RESCU-Water emphasise the dynamics of water requirements in irrigation through the use of a "bottom-up" representation of crop systems.

Thus, the underlying research questions refer both to the changes in unconstrained freshwater demand in irrigation and to the economy-wide impacts of demand-driven water deficits:

1. What is the future pressure on freshwater resources coming from irrigation water requirements with socioeconomic development?
2. How will mounting atmospheric concentrations of GHGs impact the water demand in irrigated crops?
3. What are the economy-wide and food security impacts of future demand-driven water scarcity under different climate change scenarios?

The answer to the first question enables the construction of a detailed 'no scarcity' baseline for water demand across eight crop classes by taking into account the interactions between the expansion in food demand and technological improvement. Next, the analysis for the second question determines the alterations to crop water productivity and irrigation water demand stemming from changes in climatic conditions (temperature, length of growing season and soil moisture) and CO_2 fertilisation. Finally, the water scarcity assessment corresponding to the third question builds on the findings of the previous two by exploring the multi-sectoral impacts coming from water deficits. These deficits are resulting from the unsustainable regional withdrawals implied by the economy-wide water demand baseline. The implications of climate change and water scarcity occurring simultaneously are further considered with a focus on crop production.

The analyses in this thesis refer to the use of *blue water resources*. This component represents the volumes of renewable freshwater contained in the combined surface and groundwater sources and which can be routed from one use type to another. Therefore, in scenarios constraining the use of freshwater relative to a sustainable supply threshold (3^{rd} research question), the available volumes considered in groundwater sources comprise the natural aquifer recharge and exclude the long-term stocks of fossil and non-fossil aquifers.

Although data to represent the crop uses of green water is available i.e. water naturally contained in soils, this is not directly considered due to its immobility outside crop production. Nevertheless, green water availability influences blue water demand patterns through changes in soil moisture. This effect is captured indirectly in climate change scenarios through alterations to the blue crop water productivities of crops as irrigation needs to compensate for any soil moisture deficiencies.

Because the work focuses on the demand side of the water scarcity equation, modifications to blue water supply coming from climate change are not part of the model scenarios. This approach is taken to isolate the economic effects of socioeconomic development, technological improvements and climate change on freshwater demand from the impacts of climate change on hydrological cycles and the uncertainties related to these impacts. The integrated assessment of combined freshwater demand and blue water supply changes are left for future work as these could fit into the RESCU-Water model capabilities.

Freshwater demand is expressed in withdrawals terms and not consumption. Although return flows can be significant and waste water can represent an important source of water supply, this is dependent on local conditions – the topology of users, the timing of withdrawals and return flows, the quality and reusability of freshwater. At this stage, this could not be captured within a global analysis without potentially making some largely arbitrary assumptions unsupported by evidence.

The results are presented at a national or macro-regional level. Hence, the water scarcity impacts addressed in this thesis do not consider the water deficits which are basin-specific but are averaged out through national or regional aggregation. Although the availability of gridded maps would enable the representation of crop production at a finer geographical resolution such as a river basin level, the other freshwater users are more difficult to represent in a global economic database due to the data aggregation of the underlying national accounts. At the same time, the current downscaling techniques could produce unreliable results of mapping economic activity at a fine geographical detail.

Because freshwater scarcity cannot be currently mapped in the underlying global monetary flows through assignable scarcity rents, the obtained impacts in the thesis refer to the increased scarcity relative to the base year. Hence, positive scarcity rents for freshwater as a natural resource are obtained in regions and in simulation years where water demand is constrained to match an exogenous regional supply. These scarcity rents alter the costs of water-using sectors and influence production and consumption decisions across the economy.

The water supply values are set with a long-term sustainability view i.e. upper limits for withdrawals levels are set to avoid river basin over-exploitation and to make provisions for environmental requirements. Desalination technologies are not considered as a large-scale alternative to natural freshwater supply. Hence these do not contribute to the alleviation of water scarcity in the considered period for the analysis. Also, the supply of freshwater does not make a distinction between surface- and groundwater sources.

The water scarcity impacts are captured across GDP and sectoral output but are also expressed in welfare and food security terms. For welfare, the impacts are determined through the Equivalent Variation which is a standard welfare measure taking into account the income changes determined by alterations to consumer prices. For food security, the metrics of crop output and crop prices cover the dimensions of food availability and affordability but leave out other relevant issues such as food access barriers or food supply stability.

The model simulations run in the 2004-2050 period. This time horizon is chosen so as to go beyond the timeframe of the SDGs in order to give a longer-term view on the drivers of water demand and the continued increase in pressure over the resource base post-2030. Global population may peak only in 2050 whilst the atmospheric GHG pathways start to diverge only after 2025 - by 2050, climate change incidence over water demand patterns is likely to already be noticeable with CO_2 concentration differences between the RCP2.6 and RCP8.5 pathways reaching 100ppm. Nevertheless, extending the analysis to the end of the century significantly increases the uncertainties of results from a demographic perspective but also from an economic standpoint as structural changes and technological evolution could be dramatic and are largely unforeseeable.

1.4. Significance of the study

The thesis comes at a time when there is an increasing interest and concern related to the topic of water scarcity. Water shortages have been on the World Economic Forum list of top global risks for a number of years, ranking first in terms of impact in 2015. Dealing with water deficits will thus be a matter of how scarce resources are managed: “Decision-makers will be forced to make tough choices about allocations of water that will impact users across the economy” (WEF 2015). The need for water allocation due to physical scarcity is already acknowledged in practice at a national or river basin level with a wide range of regimes implemented in both developed and developing regions.

Thus, the results of this work will provide quantified evidence not only on the importance of freshwater to economic activities and food security but also on the differences in impacts between alternative water allocation options. At the same time, the GDP projections are usually made by not assuming any constraints in the use of natural resources. The analyses presented here account for the limited availability of freshwater across multiple regions and for the feedback effect this would have on economic growth assumptions.

For climate change policy, the study captures the interactions between the incidence of demand-driven water deficits and that of climate change on crop output, and thus determines a broader picture over the future state of food security in and outside water-scarce regions. The outcomes of the climate change scenarios could thus inform on the changes in the crop production mix with important implications on nutrition. Furthermore, the results show the differentiated capacity of the major crop classes to adapt to the negative impacts of climate change through the use of irrigation.

From a methodological perspective, the RESCU-Water model development consists of several advances of the current state of the art in freshwater modelling using global economic frameworks. With research in the past decade focusing mostly on water use in irrigation, the RESCU-Water model focuses on the economy-wide representation of water by considering five self-abstracting activities (irrigation, livestock, thermal power, industrial water supply and municipal water supply) and the underlying water users supplied through distribution networks. Furthermore, the introduction of water as a distinct factor of production enables the specification of alternative water allocation regimes and allows for a sector-specific adaptation to water deficits.

Global crop water requirements under socioeconomic development and climate change are calculated for the first time using a macroeconomic framework through a "bottom-up" specification of crop production systems and crop-specific water demand. At the same time, the introduction of water-related inputs in the production technologies of irrigated crops is also improved through a clear distinction between the use of irrigation equipment and that of water as an endowment. This separation allows for a more accurate representation of water scarcity in the simulation scenarios. The RESCU-Water model database also captures improvements in the valuation of irrigation by correcting some oversimplifying assumptions made previously regarding the value-added of irrigation use.

1.5. Overview

The thesis is composed of nine chapters. Following this introduction, Chapter 2 introduces the general concepts needed to be considered in a water scarcity analysis by outlining the environmental services of freshwater, the current state of freshwater availability, the drivers of freshwater demand, and the challenges of water allocation and water pricing.

Chapter 3 reviews the past research efforts to represent the relationship between the economy and water demand and critically analyses the assessment methods dedicated to the economic impacts of water scarcity. A broader view on modelling frameworks is taken by considering both biophysical and economic models (partial and general equilibrium) so as to gain an understanding of the potential synergies between the different approaches.

Chapter 4 feeds on the literature review done in the previous chapter and identifies the main research gaps in addressing the issue of demand-driven water scarcity by making the case for further model development. The RESCU-Water modelling framework is then described in detail. The water accounting and the modifications to the GTAP database to fit the requirements of the model are presented next in Chapter 5.

The applications of the RESCU-Water model are spread across three results chapters with each addressing a separate research question. Chapter 6 assesses the relationship between irrigation water requirements and socioeconomic development through the consideration of three alternative development futures of the Shared Socioeconomic Pathways framework (SSP1, SSP2 and SSP5). Technological advancements are also included by differentiating yield improvements by crop class and by the irrigated and rainfed growing methods.

Chapter 7 assesses the impacts of climate change on blue water productivity in crop production. The scenarios determine the alterations to irrigation water requirements under the SSP2 storyline for two GHG concentration pathways (RCP2.6 and RCP8.5). Climate change incidence is accounted for at multiple levels – yields, soil moisture and carbon fertilisation. The uncertainty of climatic responses to mounting GHG concentrations is considered through the use of output data from three global circulation models.

The impacts of demand-driven water scarcity on economic activity and food security are determined in Chapter 8. A water demand baseline across the main five user categories is first constructed by adding freshwater demand projections for non-crop users to the unconstrained crop water demand from Chapter 6. The consideration of water deficits is done in areas exceeding long-term sustainable withdrawal levels (India, South Asia, Middle East and Northern Africa) in the 2004-2050 timeframe. The model scenarios use four alternative allocation methods to capture the trade-offs between macroeconomic effects and food security outcomes under different water management options. The interactions between water deficits and climate change are also considered by using three climate change variants (no climate change, RCP2.6 and RCP8.5) affecting irrigation water demand.

Whilst each of the chapters 6-8 comprises a discussion of results, Chapter 9 condenses the main findings and discusses their implications for policy making. The case for further research is also made in this concluding chapter.

Chapter 2. Concepts and definitions

2.1. Introduction

The issue of water scarcity is tied both to how much freshwater is available for human use and also to the extent to which freshwater resources are abstracted from the environment. Therefore, water-scarce regions need not necessarily be in a dry climate but are areas in which withdrawal levels represent a significant share of the resource base, a situation which leads to the risk of imbalances between the demand and the natural supply of water. The aim of this chapter is thus to present the current state of water scarcity across world regions, and to introduce the prevailing conventions and estimation methods used to reveal the pressure over the resource base coming from human consumptive uses.

On the supply side of the water scarcity equation, freshwater resource availability is qualified in Section 2.2 through the use of the renewability and human accessibility criteria. The overall environmental services conditional upon the availability of freshwater are also taken into account. These considerations help indicate the importance of adopting a long-term view regarding the sustainability of freshwater abstractions relative to the extractable renewable resource base. On the demand side, much of the past evolution of global abstraction levels has been explained by the expansion of withdrawals for irrigation. However, regions differ in their current water use patterns both according to their socioeconomic development stage and to the intensity of water use inside and outside agriculture. Section 2.3 presents these differences with the intention of identifying the drivers of future water demand.

The main indicators used to defined water scarcity in global-level assessments are discussed in Section 2.4. Given the aim of the thesis to explore the economic impacts of water scarcity under different water allocation regimes, the concepts of *water allocative efficiency* and *water scarcity rents* are introduced in Section 2.5. This section also includes the different water charging methods and the constraints of considering an explicit water scarcity value as a means of allocating scarce freshwater resources across economic activities.

2.2. Freshwater availability for human appropriation

The availability measures can refer to both the stock and the flow dimensions of water resources. As a *stock* resource, the total amount of water on the planet is fixed and is mostly stored in long term-reservoirs. Water resources are then further classified through the salinity criteria into *freshwater* and *salty water*. It is freshwater that provides many important ecosystem services and on which the well-being of humans and that of other species depend.

Freshwater represents only 2.5% of all water available on the planet, the rest being stored in oceans, seas and salty aquifers. Furthermore, just 30% or 10 600 000 km^3 of freshwater stocks are theoretically accessible (Table 2.1) the rest being locked in glaciers and permanent snow. Most of the accessible freshwater is stored in aquifers whilst a very small fraction is available as surface water (rivers and lakes).

Table 2.1 - Storage of global freshwater resources

Freshwater source	Volume (km^3)	% of total accessible	% of total freshwater
Total accessible	10,665,110		30.43%
Groundwater	10,530,000	99.02%	30.10%
Lakes	91,000	0.86%	0.26%
Swamp water	11,470	0.11%	0.03%
Rivers	2,120	0.02%	0.006%
Ice caps, Glaciers, & Permanent Snow	24,064,000	-	68.70%
Other - non accessible blue water	316,500	-	0.91%
Soil moisture	16,500		0.05%
Atmosphere	12,900		0.04%
Biological water	1,120		0.003%

Source: Shiklomanov (1993)

Natural transfers between freshwater and salty water stocks are occurring in both ways due to the global water cycle which operates as a closed system (Figure 2.1) - about 10% of oceanic evaporation is converted into land precipitation (Gleick 2003). At the same time, oceans and seas get replenished through discharge of rivers (B_a'). Land precipitation inflows are broken down into the *green* and *blue* water components. Green water accounts for the amounts of freshwater that are absorbed by soils and then lost through plant evapotranspiration (ET_a). Blue water represents the volume that recharges rivers, lakes and aquifers. This last component consists of surface run-off (B_a) and groundwater recharge (RO_a). It is the blue water component together with groundwater stocks that is the object of water resource management as these comprise the freshwater volumes that can be directed to different uses, including economic activities. Hence, humans can influence the global water cycle through freshwater extraction from river basins (U_a) or fossil groundwater (U_{an}), through return flows ($B_{a''}$) and through evaporative consumption (C_a).

Precipitation minus all natural evaporative processes (natural evapotranspiration, canopy and surface water evaporation) represents the *renewable freshwater resources* or the flow dimension of freshwater. There are large variations regarding the calculation of long-term mean total renewable water resources (TRWR). The values are generally determined through global water balance models and fall within the 33 500 – 47 000 km^3 range (UNEP 2005, Chapter 7), with the FAO Aquastat using 42 810 km^3 as a central value (FAO 2016).

Regardless of this variation, TRWR volumes are small enough that it would take these more than a thousand years to recharge the aquifer stocks (Shiklomanov 1993). Recharge rates are not only dependent on the presence of renewable resources but also on the infiltration process from surface to groundwater. Therefore, any human appropriation exceeding renewable resource quantities leads to groundwater depletion and can imply a lengthy recharge period once the over-exploitation ceases or even an irreversibility of the impacts if withdrawals are made from fossil groundwater.

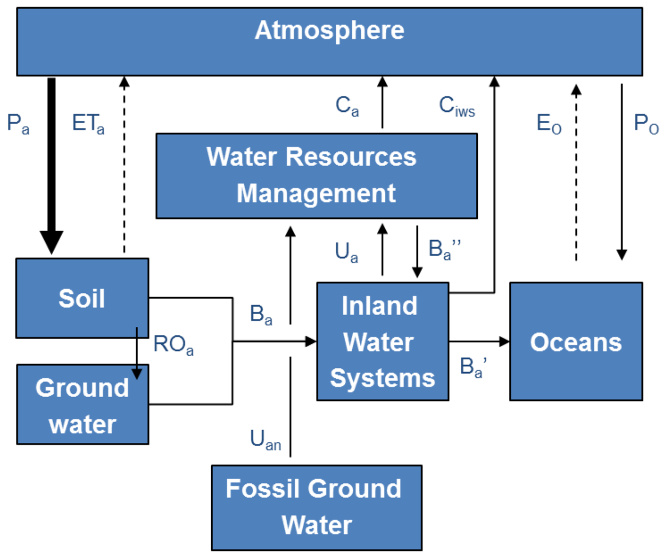
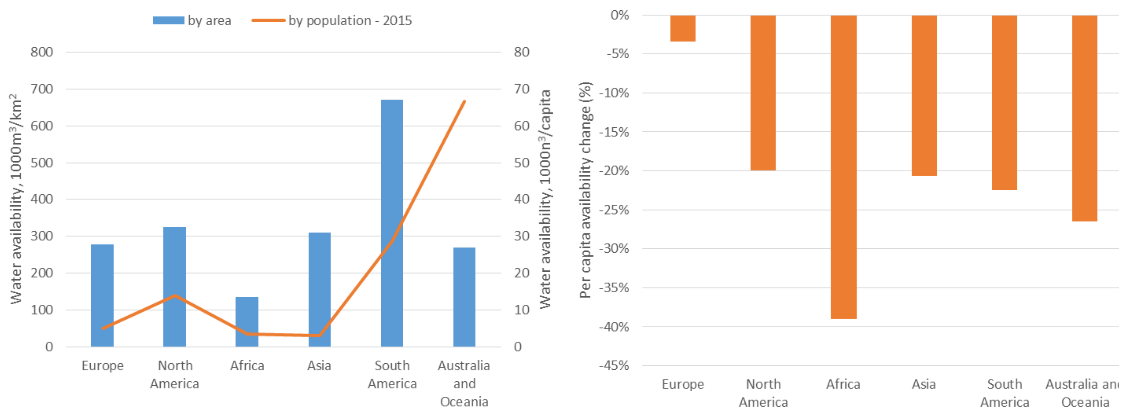


Figure 2.1 - Global water cycle

Source: adapted from UNEP (2005b)

Renewable freshwater resources are distributed unequally across the globe due to differences in land precipitation levels across drainage basins. Hence, some extended geographical areas are confronted with low water availability per unit of land area (Africa, Asia), whilst in others, freshwater flows are plentiful (South America) - Figure 2.2a. When factoring in the global population distribution, differences between regions in terms of per capita availability are even higher, with a factor of more than a hundred between water-rich and water-poor regions. Furthermore, much of the global population growth from the past century occurred in areas which already have a low water availability. Consequently, per capita endowments in Africa and Asia have decreased significantly especially in recent decades (Figure 2.2b). With current population projections, water availability per capita is expected to continue to decline in many water-challenged regions.



(a) (b)

Figure 2.2 - Renewable water resources availability by continent (a) and per capita availability changes 1995-2015 (b)

Data source: water availability and land surface data (Shiklomanov 1999), population (World Bank)

Human appropriation of the entirety of TRWR is technically challenging and only a third of these volumes is estimated to be accessible (Postel et al. 1996). This constraint is due to the lack of proximity of human settlements to river basins but also to temporal imbalances between human demand and natural supply. However, significant increases in accessible resources can be obtained through the development of water storage infrastructure. Current reservoir capacity has been estimated to be in the order of 8 000 km^3 globally (Biemans et al. 2011) representing thus a significant share of total flows. Interbasin water transfers are also emerging as a large-scale solution to increase freshwater availability in water-poor areas – see the *South-North Water Transfer Project* in China and the *Rivers Inter-link Project* in India.

Other environmental dimensions of freshwater may also influence the calculations of water availability for human abstraction (Table 2.2). Besides the consumptive uses[1], freshwater is essential to other ecosystem functions contributing to human well-being (UNEP 2005b). Freshwater services thus cover all four dimensions of the Millennium Ecosystem Assessment framework – provisioning, regulating, cultural and supporting[2]. Other than withdrawals for household, industrial and agricultural use, freshwater acts as a provisioning service for hydropower generation and inland water transportation. At the same time, a minimum

[1] These are also referred to as offstream uses implying the physical abstraction of water from groundwater or surface sources.
[2] This ecosystem services classification has been carried forward in the new IPBES conceptual framework (Díaz et al. 2015)

freshwater flow is required for the protection of ecosystem health and biodiversity, but also for other purposes such as recreation.

Smakhtin et al. (2004) introduced the concept of "environmental flow requirements" (EFR) representing the minimum surface water flows for ensuring the health of aquatic systems with volumes in the order of 20-50% of mean annual run-off. These provisions for environmental protection imply that a significant share of renewable freshwater resources may need to be deducted from the total sustainable supply limits. The calculation of EFRs at a global level is still at an early stage (Gerten et al. 2013). Nevertheless, to arrive at a sustainable quantity for human use, several methods have emerged (Pastor et al. 2014) with the potential of integrating the findings in global water scarcity assessments in the future.

Table 2.2 - Freshwater ecosystem services

Provisioning Services	**Regulatory Services**
• Water (quantity and quality) for consumptive use (drinking, domestic use, and agriculture and industrial use) • Water for non-consumptive use (hydropower and transport/navigation) • Aquatic organisms for food and medicines	• Maintenance of water quality (natural filtration and treatment) • Buffering of flood flows, erosion control through water/land interactions and flood control infrastructure
Cultural Services	**Supporting Services**
• Recreation (river rafting, kayaking, hiking, and fishing as a sport) • Tourism (river viewing) • Existence values (personal satisfaction from free-flowing rivers)	• Role in nutrient cycling (floodplain fertility), primary production • Biodiversity - predator/prey relationships and ecosystem resilience

Source: (UNEP 2005a)

Through withdrawals and the related infrastructure composed of dams and canals, the provisioning dimension is increasingly interfering at a large scale with the natural river discharge, limiting freshwater availability for other service types. Consequently, the growth in water demand for the different human uses could also imply trade-offs between environmental and socioeconomic objectives and may require specific policy intervention for balancing the two (see the Murray-Darling government buyback programme - Dixon et al. 2011).

2.3. Freshwater uses

2.3.1. Withdrawals and consumption

In freshwater use reporting, freshwater "demand" or "use" can refer to both *withdrawals* and *consumption*. Withdrawals represent the volumes that are extracted from a freshwater source with the aim of meeting human needs through a consumptive use. These can be taken from river run-off but also from the existing stocks stored in aquifers. Consumption is the fraction of withdrawals which is unavoidably lost through drinking, absorption or evaporation.

The relationship between withdrawals and consumption is determined by how efficiently freshwater is used. More than half of all water abstracted is returned to surface run-off (WWAP 2017). Irrigated crop production faces the largest inefficiencies with up to two-thirds of withdrawn water not being used for effective crop growth. Also, in many cases, the return flow is of a different quality than that of withdrawn water. Inefficiencies in irrigation lead to important volumes of water being contaminated with nutrients and pesticides and returned to river streams generating eutrophication and other pollution issues in regions practicing intensive agriculture (see, for instance, Mekonnen & Hoekstra 2010 or Chapagain & Hoekstra 2011).

Although return flows and wastewater can be an important source of water supply, analyses at a global level do not currently allow for an accurate representation of return flow reusability from a temporal availability and water quality perspective. To the author's best knowledge, there isn't any global quantification of return flow potential. Any appreciation in this regard would be influenced by significant uncertainties regarding the user topology within river basins, the timing of uses of the different demand agents, and the opportunity costs of water treatment requirements which are case-specific (UNESCO 2017). Therefore, due to data limitations arising from the scale of analysis, in this thesis water demand refers to withdrawals, in line with all other global assessments focused on water scarcity (see Chapter 3), and implicitly does not take into account return flows.

2.3.2. Freshwater withdrawals patterns

Currently, total global withdrawals represent 8-10% of total renewable freshwater resources, depending on water use calculation methodologies and the resource base estimations. The use of water has grown sixfold during the 20th century, or twice as fast as the global population (WMO 1997), indicating that withdrawals are linked to demographic evolution but also to economic development (UNEP 2005).

Globally, 70% all water withdrawals go into agriculture, 19% to industrial self-abstracting sectors and 11% to municipal and household use. Significant differences can be observed between regions (Figure 2.3). In most developing countries, water for irrigation represents by far the largest user. In industrialised countries, the weights are shifted to industrial and municipal use, with the USA, for instance, allocating only 40% to agriculture despite being an irrigation-intensive region.

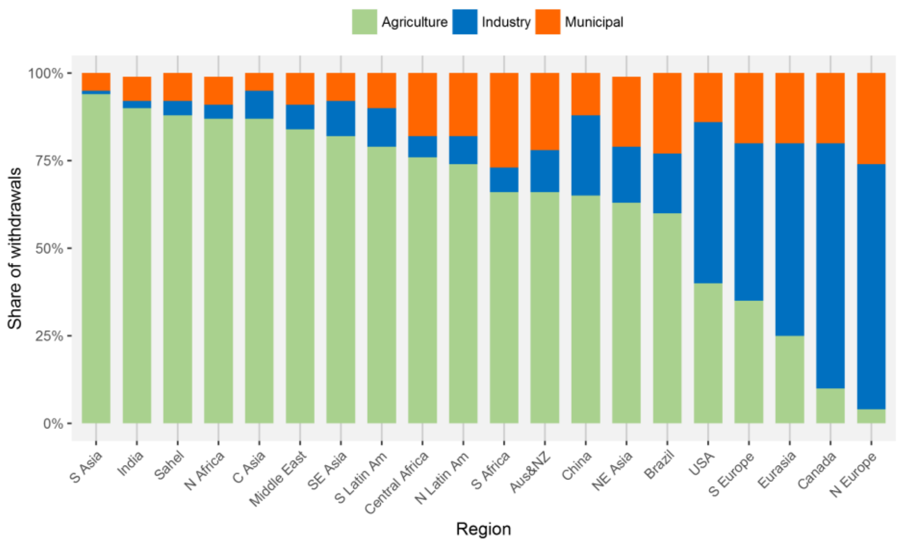


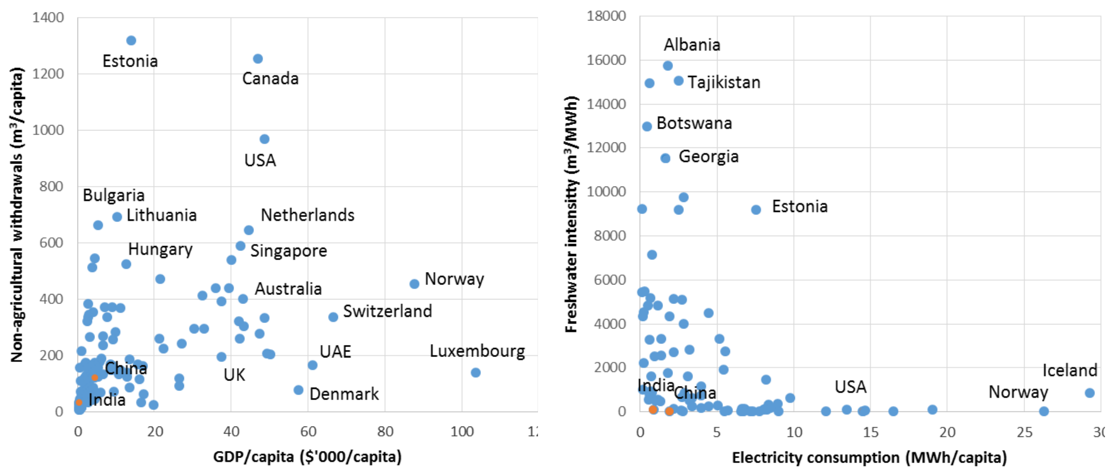
Figure 2.3 - Freshwater withdrawals by use type (2000-2005)

Data source: FAO (2016)

Industrial withdrawals are dominated by the energy sector which is estimated to account for 75% of all industrial water uses (IEA 2012). Energy production requires water for thermal power plant cooling and fossil fuel extraction. Total withdrawals in 2010 were estimated at 583 km^3 or about 15% of total global withdrawals. Out of these, 540 km^3 were dedicated to power plant cooling alone. Outside the energy sector, important volumes of water are employed in manufacturing, mining, chemicals and paper sectors for a number of functions such as processing, diluting or washing.

Municipal withdrawals are linked to household demand but also to the freshwater use in urban irrigation, urban industry and services. Data required to untangle these specific uses are rarely available, and usually it is assumed that population and income per capita are the most important determinants of overall withdrawals (Wada et al. 2016). Regarding domestic water withdrawals, there is a notable difference between urban and rural populations, with the former's demand level being much higher due to wider possibilities of use but also due to the convenience of supply through distribution systems (Hayashi et al. 2013).

Figure 2.4 (a) illustrates that many regions are still in their early days of industrial and municipal withdrawals. One explanation is that these are characterised by a low electricity consumption per capita (Figure 2.4 b), which limits the current freshwater demand for power plant cooling, but also by low urbanisation rates and under-developed industrial sectors. For industrialised regions, there is an important variation in terms of water intensity outside agriculture. For instance, for similar income levels, USA and Denmark have a demand per capita difference of almost 20 times, this being influenced by the technological mix of power generation, industrial structure and water use efficiencies. Nevertheless, as countries continue to develop, a growth in freshwater demand from non-agricultural sectors is expected to occur (Marchal et al. 2011). Economic development through industrialisation will require more water and energy (subsequently implying more water for thermal cooling and primary energy extraction). Growth in income per capita and rapid urbanisation will also result in the growth of municipal water demand.



(a) Per capita non-agricultural withdrawals (b) Power production freshwater intensity

Figure 2.4 - Non-agricultural withdrawals and development 2000-2005

Data source: withdrawals (FAO 2016), GDP/capita (World Bank) and electricity production (IEA Electricity Information Statistics)

2.3.3. Withdrawals data issues

Time series regarding freshwater withdrawals by user type for a global level assessment are usually incomplete or even absent. Data for one single year is often estimated by combining available national statistics with modelling exercises and expert judgement. Hence, withdrawals data inconsistencies and uncertainties are introduced through the use of different input data, estimation methodologies and withdrawal structuring by user type.

The FAO Aquastat database, as the main source for global freshwater use statistics, divides water uses in three groups (agriculture, industrial and municipal) based on the supply mode criteria (industrial water is represented by self-abstracting sectors whilst municipal water accounts for the volumes supplied through distribution networks). Therefore, one user type such as industrial processes can be spread across the two supply modes. At the same time, other withdrawal calculation methods are more modelling-focused (see Wada et al. 2016 for an overview) and emphasise the overall water use by user type rather than by the supply mode.

As the largest freshwater user, irrigation is an important source of uncertainty in determining current withdrawal levels. Given the distributed nature of irrigation, blue water uses for crop production are usually derived through modelling exercises (Siebert & Döll 2010; Hanasaki et al. 2008; Fischer et al. 2007; Rost et al. 2008; Wada et al. 2011). These values are assessed through crop models which calculate crop water uses by considering local climatic conditions. Evapotranspiration is usually calculated using either the Penman-Monteith or the Priestley-Taylor approaches (Allen et al. 1998) which account for temperature, humidity, wind speed and solar radiation but which can lead to different outcomes in terms of crop water requirements for optimal growth (Utset et al. 2004; Suleiman & Hoogenboom 2007). At the same time, crop models usually imply an optimal application of irrigation through the crop growth stages (Siebert & Döll 2010), an assumption which is almost certainly different from true growing conditions. Furthermore, these calculations rely on the of use global gridded maps (e.g. Monfreda et al. 2008; Portmann et al. 2010) which are constructed through varying methods of combining remote-sensing methods and national statistics, influencing evapotranspiration calculation outcomes (Kalma et al. 2008; Glenn et al. 2010). Finally, given the high losses in irrigation, withdrawal levels for crop production are very sensitive to irrigation efficiency estimation. Values for efficiencies can vary from one study to another as these may use different data and assumptions regarding the performance at the conveyance and field application levels (Döll & Siebert 2002; Rohwer et al. 2007; Frenken & Gillet 2012) but also regarding crop management practices (Jägermeyr et al. 2015).

Therefore, for the year 2000, in these studies, results can vary by of hundreds of km^3 (for instance, 2057 km^3 in Wada et al. 2011 and 2630 km^3 in Fischer et al. 2007). The variation in these estimations is important, being equal to, for instance, total withdrawals for energy production, and thus significantly influences any demand-driven scarcity calculations. These variations are also important in determining the potential for re-allocation of freshwater resources between users. The more water use in irrigation the lower the water productivity in crop production; hence, more water can be re-allocated away from crop production for the same outcome in crop output changes.

2.4. Freshwater scarcity indicators

The measurement of global water scarcity has been a central topic in many studies (Shiklomanov & Balonishnikova 2003; Vorosmarty 2000; JOSEPH Alcamo et al. 2003; Hanasaki et al. 2008). Most of these define the state of water scarcity as one in which total human water demand exceeds the renewable water supply.

The main two metrics used in water scarcity assessments are the *Water Stress Index* (WSI) and the *Withdrawals to Availability* (WTA) ratio. WSI was introduced by Falkenmark & Widstrand (1992) and relates available blue water resources to water requirements calculated on a per capita basis. Regions with resources below 1 700 m^3/capita are considered to be under "water stress" and those below 1 000 m^3/capita to be under "water scarcity". These stress and scarcity thresholds were set starting from theoretical computations of basic human water requirements. As an alternative, Alcamo et al. (2003) introduced the WTA metric as the ratio between estimated actual withdrawals and the available renewable freshwater. A WTA value exceeding 20% and 40% characterises an area as being under moderate and severe water stress respectively. A threshold of 75% for the WTA indicator was added in Molden (2007) to denote a state of *physical water scarcity* characterised by human withdrawals exceeding sustainable limits.

Due to the dual stock-flow dimension of freshwater resources, there is an ongoing debate regarding the accuracy in establishing the state of freshwater scarcity around the globe judged through the lens of renewable freshwater resources distribution as done for the WSI and WTA calculations. Damkjaer & Taylor (2017), for instance, make a case for a more holistic metric which takes into account the availability of storage to average out temporal fluctuations. Gleick & Palaniappan (2010) discuss the concept of "peak water" withdrawals, a parallel to that of peak oil, in which withdrawals limitations are analysed from three different angles – renewable water, non-renewable water and ecological water.

Whilst acknowledging the limitations of using an aggregate measure in a global-level assessment, the definitions and the metrics adopted in this thesis to determine the state of water scarcity across world regions are in line with those in Alcamo et al. (2003) and Molden (2007). Thus, a region is considered to be water-scarce when total human withdrawals exceed a substantial share of the region's total renewable water resources (TRWR) calculated as the sum of total internal resources coming from precipitation and of inflows from neighbouring regions. In addition, regions with persistent and wide-spread river basin exploitation (withdrawals exceeding river basin recharge rates) are also considered to be water-scarce.

2.5. Freshwater allocation

It is beyond the scope of this thesis to discuss the feasibility regarding a large-scale implementation of a specific freshwater allocation mechanism. Nevertheless, it is important to acknowledge that in conditions of water scarcity, combined with temporary or permanent changes in patterns of freshwater demand, a re-allocation of resources between users is likely to be necessary. In the absence of an explicit mechanism, upstream users would have a natural priority as these would be the first able to access flows and by this, could potentially curtail the required supply for downstream users.

From a welfare perspective, the issue of implementing an allocation method is tied to economic efficiency objectives i.e. how to make resources available to users such that the net benefits from water use are maximised, or to social and equity objectives i.e. how to enable access to freshwater resources for users which may not gain access to sufficient resources without intervention. In economic theory, an efficient allocation of a scarce natural resource across economic activities is one in which the marginal value product or marginal benefit in using that resource is equal across all users (Perman 2003 p.107). This resource allocation is said to be Pareto optimal as no further welfare improvement can be made i.e. any changes to the resource allocation could not make one party better off without making another worse off. This outcome is achievable by setting one single price of the resource for all users. From the partial equilibrium standpoint of a single-resource market, the optimal price is located at the intersection between the resource demand and supply curves. Setting a price at any other given level would lead to welfare losses (Perman 2003 p.121). In this market, the resource demand curve is defined by the aggregate marginal benefit of using that resource, whereas the supply curve is determined by the marginal cost of supplying one additional unit of the resource.

This theory is applicable to perfect market conditions in which the resource is private and homogenous, information is perfect and all agents are price takers. For freshwater, markets implemented with the aim of allocative efficiency deviate from these conditions. First, freshwater in nature is not a pure private good, but often has the characteristics of a non-excludable and depletable good subject to competition and congestion (Barbier 2004). Second, as in the case of many other goods, it is difficult to determine a supply and demand curve due to imperfect information on costs of supply but also due to the difficulty in quantifying the benefits of freshwater use. Next, freshwater may not be a homogenous good and hence the cost of supply might differ based on the quality standards of each user type (Dinar et al. 1997). At the same time, the cost of supply might depend on the location of each user and therefore separate pricing would be required to reflect the differentiated marginal costs by location. Finally, the organisation of water supply activities lends itself to becoming that of a natural monopoly with implications for water pricing. This is due to the large-scale infrastructure requirements covering large geographical areas, the long-term investment horizons and the possible economies of scale of freshwater provision (Dinar et al. 1997).

In practice, alternative approaches are used to internalise the value of freshwater supply. These depend on the way freshwater is perceived (as a public or private good) but also on the cost-recovery targets of the supplier. The valuation through explicit water pricing could be limited to cover only the supply cost or could be extended to include the full economic cost or even the environmental externalities e.g. pollution.

Volumetric charging methods consist of pricing freshwater supply by the actual volumes used and imply the existence of a measurement infrastructure and recurring meter readings. Among these methods, marginal-cost pricing (MCP) is the option to adhere to the principle of economic efficiency. However, given the likely natural monopoly structure of the market, MCP does not lead to full cost recovery unless the prices reflect the long-run marginal cost. Full cost recovery can also be achieved through average cost pricing (ACP), but in this case, prices are set above the marginal cost and hence allocative efficiency is not achieved. The allocation can also be made through regulatory means by setting use quotas across users (user-based allocation) which may have reduced prices for low volumes used. This last approach treats water as a basic need and can promote equity objectives by supplying freshwater at low cost to water-deficient users or low-income households.

In the absence of metering information, freshwater uses can be charged indirectly, through non-volumetric methods, either through flat rates or through the use of indirect metrics providing an indication of water use levels e.g. duration of use, area pricing. Nevertheless, these methods are less effective in influencing consumer behaviour and lead to a sub-optimal use of water by potentially encouraging an excessive demand in low-value uses.

It is important to highlight that freshwater supply in areas which are not water constrained is limited by the capacity of the underlying infrastructure which is in itself economically scarce due to investment requirements. Therefore, any allocative efficiency through pricing mechanisms would seek to maximise economic output with respect to the existing supply infrastructure at any point in time. In areas where demand levels exceed natural supply, with allocative efficiency, the value of water would be larger than the cost of supply by including water scarcity rents. This value together with other potential externalities reflects the 'cost to society' (Bosworth & Perry 2004). The inclusion of scarcity in price signals could be done through markets where water use rights are traded and where the clearing price reflects the point at which the benefit of using one additional water resource unit is equal across all competing uses.

The scarcity value raises the optimal price of freshwater due to the modification of the supply curve to become perfectly inelastic at the upper limit of freshwater availability Q* (Figure 2.5). By increasing the price to P*, the total scarcity value is included in the social surplus through the scarcity rents obtained in the water rights market. Also, the collection of these rents could have distributional impacts depending on the initial structure of property rights. For instance, water use rights can be tied to land ownership and thus farmers could be rewarded for giving up water withdrawals in favour of higher-value uses such as municipal water supply.

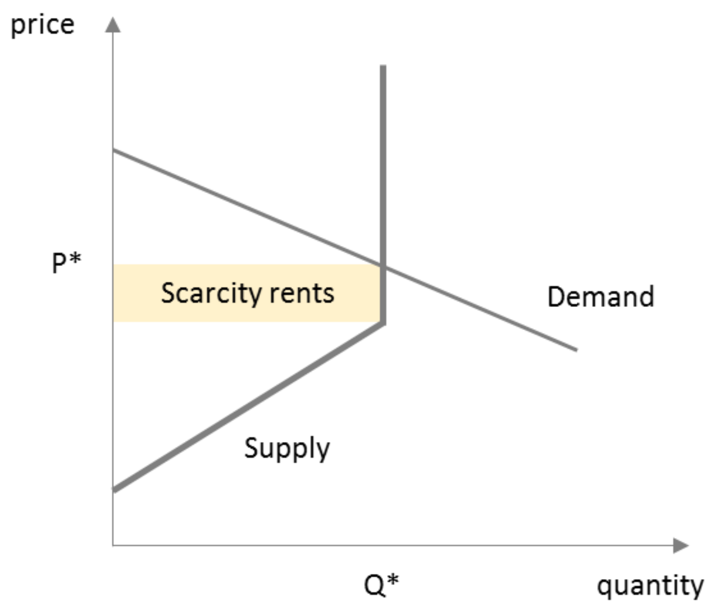


Figure 2.5 - Scarcity rents in water markets

There are a few, at least theoretical, advantages in using water markets to allocate resources under scarcity conditions (Dinar et al. 1997). With scarcity levels potentially varying across seasons and years, water markets allow for flexibility in freshwater allocation when supply and demand conditions change. Therefore, the trading of water rights can be further considered as an adaptation method to the effects of climate change on the demand and the availability of water (Rosegrant et al. 2014). At the same time, revealed scarcity values enable users to measure the freshwater opportunity costs and thus can make decisions to invest in water conservation technologies or storage capacity. Also, when users are compensated for giving up water withdrawals, re-allocation can become more acceptable for parties having to reduce their water-related activities, again, this being dependent on the attribution of water use rights.

Nevertheless, the implementation of a water rights market includes a number of pre-requisites – the availability of volumetric water data, an initial assignment of water rights to users, an infrastructure to allow the physical transfer withdrawals from one user to another and an institutional capacity to enforce withdrawal rules (Rosegrant & Binswanger 1994). These conditions make the introduction of tradable permits difficult, however, still possible, as the market setup in the Murray-Darling basin illustrates (Turral et al. 2005).

In practice, a considerable number of countries are already implementing a form of water allocation (OECD 2015). The allocation regimes emerged either through direct policy intervention acknowledging the limited water availability in a top-down manner or through a grassroots multiplication of farm-level initiatives as in the case of India (Saleth 2014). Therefore, allocation rules can be both formal with clear institutional and use rights arrangements and informal through ad-hoc water market arrangements. Where a legal framework is in place, the allocation is frequently determined by user prioritisation (see examples in Figure 2.6). Importantly, water entitlements are not often awarded in perpetuity and are unbundled from other property rights (e.g. land), indicating the potential for a long-run flexibility in the water allocation rules. In terms of formal water rights trading, whilst in most cases entitlements can be either transferred or traded, these transactions require a prior approval from the competent authority (e.g. licencing authority, environmental agency).

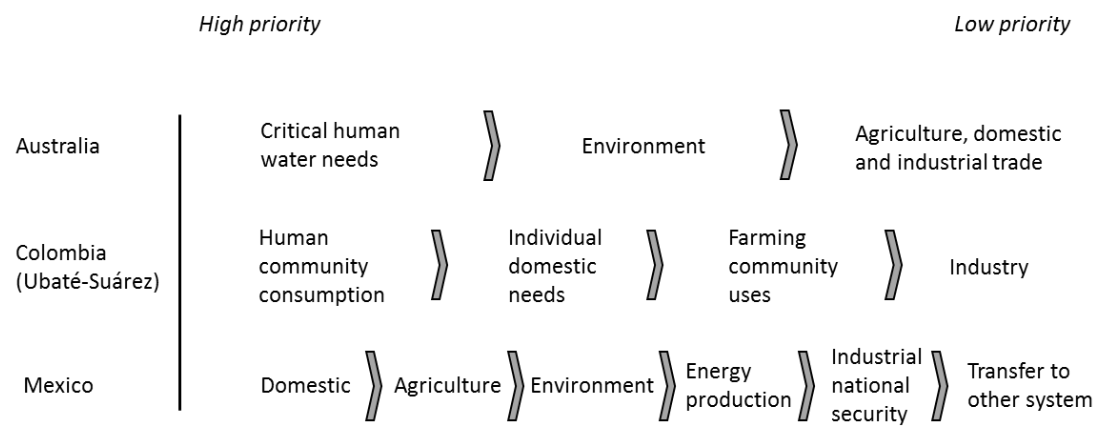


Figure 2.6 - Examples of water user prioritisation

Source: adapted from OECD (2015)

2.6. Summary

Assessing the current state of water scarcity is not trivial notably at a global level where a large set of uncertainties regarding both the supply and demand of freshwater resources are present. On the supply side, figures for freshwater water availability are interpretable as these depend on the constraints factored in. The uneven distribution of renewable resources both temporally and spatially renders a large share of the resource base un-accessible. However, human intervention through dams and large-scale water transfer schemes can influence these figures quite significantly. The calculation of accessible supply is also affected by whether the freshwater requirements for other environmental services are factored in. On the demand side, global water uses are usually estimated and are thus subject to data uncertainties and assumptions introduced through the underlying modelling efforts and expert judgement.

Current data shows that there are large discrepancies between developed and developing regions in terms of water use patterns, with developing regions allocating most withdrawals to irrigation purposes. Thus, continued socioeconomic development has the potential to increase demand outside crop production leading to increased competition from a wide range of users in water-scarce regions, notably in Asia and Africa.

The existence of competition due to physical water scarcity raises the question of how the limited renewable freshwater resources will be allocated across users. The reflection of the social cost of water in use patterns depends on whether water scarcity is acknowledged and embedded in the water prices paid by users. Therefore, in a global level analysis, it is difficult to assume a method promoting allocative efficiency as being generally a feasible solution. Due to the nature of freshwater supply which can be seen both as a basic human right and private good, equity or other social objectives can make user-based allocation methods preferable. Nevertheless, existing instances of water rights markets illustrate that water allocation based on scarcity price signals is possible. These markets are however dependent on the existence of a strong institutional framework and on the development of a conveyance infrastructure allowing for the transfer of significant water volumes between distant users.

Chapter 3. Freshwater modelling in existing large-scale frameworks

3.1. Introduction

This chapter analyses past efforts to model water demand and the importance of water scarcity in connection with economic activities. The aim of this review is to present the state-of-the-art in: ***i)*** the representation of the relationship between the economy and water use, ***ii)*** the construction of water demand projections in a world with limited water availability, and ***iii)*** the inclusion of demand-driven water scarcity as a determinant in the allocation of water resources and in the economy-wide production and consumption choices.

The existing modelling frameworks addressing the issues of water use dynamics and water scarcity can be classified based on whether these have any consideration of market price signals as a determinant of water demand. In the first category (biophysical models) the evolution of freshwater demand levels is obtained through the extrapolation of past trends or through the convergence of water use patterns between developed and developing regions. Demand is therefore not influenced by limitations in freshwater supply. Water scarcity is revealed through demand-supply imbalances calculated as absolute figures of water shortages, or through the use of scarcity indicators, but does not lead to any measured economic impacts. Nevertheless, these frameworks are valuable in determining baseline projections for unconstrained water demand under different socioeconomic development and policy scenarios. Also, some of these models integrate hydrological information at a detailed geographical level (down to a 0.5° resolution) and allow for a more accurate representation of scarcity driven by supply-side changes as in the case of climate change and its impact on run-off.

In the second category (economic models), prices determine the way resources are allocated to a set of markets or the entire economy according to an optimisation principle, e.g. cost minimisation or profit maximisation. In these models, the focus is placed on production technologies in which freshwater is considered either *explicitly* as a stand-alone market factor with an attached market price, *implicitly* as a complement to other factors for which the market value is more readily available, or as a *physical constraint* to production without any price associated. Economic modelling frameworks have the capacity to influence water demand levels through changes in water-related costs of productive sectors – these changes have an impact on the price and consequently on the demand of water-intensive commodities.

Although these two categories of modelling methods overlap in terms of their function to determine water uses in water scarcity assessments, they can also be considered complementary in detailing the two sides of water shortages – demand (economic models) and supply (hydrological models). The first category is capable of determining the implications of water resources scarcity for economic output and welfare by factoring in adaptation measures to water use constraints, whilst the second can reveal changes in water availability coming from biophysical drivers, e.g. changes in precipitation patterns coming from climate change. Also, the water demand projections determined in the biophysical models reviewed below can also be relevant in the construction of a water demand baseline necessary in water scarcity analyses. Economic models can thus be calibrated using the output of these projections.

The chapter is structured as follows. In Section 3.2, the biophysical models are surveyed through their characteristics of capturing the relationship between water demand and socioeconomic development by emphasising the differences between the considered frameworks. Next, given the focus of this thesis on the economic impacts of demand-driven water scarcity, the review expands more on the economic modelling efforts by discussing global economic models individually in Section 3.3. A discussion on the current state-of-the-art in economy-wide water modelling is also included in this section. The resulting knowledge gap in water scarcity assessments and the case for further modelling development are presented in Section 3.4. Section 3.5 draws conclusions regarding points i)-iii) above.

3.2. Biophysical modelling

The biophysical nature of the models considered in this section is given by their capacity to capture the way the global hydrological cycle translates into run-off levels and soil water balances. These frameworks are powerful in determining water availability changes, notably as a function of climate change (Schewe et al. 2014). However, their relevance in water scarcity evaluations is that these also include calculations of total water demand. In most cases, both availability and demand are calculated at a high spatial resolution reflecting thus the capacity of hydrological modelling to express changes in run-off at a high geographical resolution.

Water scarcity is revealed by these models as ratios of total demand relative to availability - mainly through the Withdrawals to Availability (WTA) ratio as introduced in Alcamo et al. (2003). Therefore, these frameworks are capable of a more precise representation of the location and the number of people living in conditions of water stress. Nevertheless, projections of water use are generally not constrained by any possible water deficits as these models do not consider any allocation mechanism to cope with excess demand obtained through the specification of an upper withdrawal limit.

Water demand in these models is typically structured around three broad categories– agricultural, industrial and municipal -, with the level of detail regarding sub-components in each category varying from one study to another. Table 3.1 offers an overview of global modelling frameworks by showing how water uses are structured. Several studies using these models have focused on the issue of future water scarcity by considering the evolution of water demand given a set of scenarios related to socioeconomic development (Shiklomanov & Balonishnikova 2003; Alcamo et al. 2007; Shen et al. 2008; Wada & Bierkens 2014; Wada et al. 2016; JOSEPH Alcamo et al. 2003; Hanasaki et al. 2013), climate change impacts (Arnell 2004; Arnell et al. 2014) and climate change policy (Hejazi et al. 2014). Future demand in these analyses is usually explained through the distinct dynamics of the individual user types.

Agricultural water demand generally refers to irrigation water requirements. Most frameworks have a “bottom-up” representation of irrigation demand as the underlying drivers are easier to disentangle compared to other water-using sectors. Demand values for irrigation water are determined by the area of land equipped with irrigation multiplied by a water intensity per unit of land and an irrigation efficiency parameter. The area and water intensities can be considered as aggregates across all crops (WBM; Shiklomanov & Balonishnikova 2003; Shen et al. 2008) or can be differentiated by crop type to reflect the variation of cropping patterns and crop-specific water requirements across grid-cells (H08, WaterGAP, PCR-GLOBWB, Hayashi et al. 2013). Values for irrigated land areas and irrigation efficiencies are obtained from global crop maps such as those in Döll & Siebert (2000), Monfreda et al. (2008) or Portmann et al. (2010). Irrigation efficiencies refer to water losses at the conveyance and field-application stages and therefore reflect the heterogeneity of irrigation infrastructure across regions (river basins, countries or macro-regions). Values are taken from a range of estimates (e.g. Döll & Siebert 2002; Rost et al. 2008a; Rohwer et al. 2007) and therefore can lead to significant variations in irrigation water demand across water assessment studies.

Demand projections for irrigation are driven by an exogenous evolution of food demand (Shiklomanov & Balonishnikova 2003; Vorosmarty 2000;) or by changes in population (Shen et al. 2008). Other scenarios for future use focus on the relationship between water demand and biofuel production as a climate change mitigation measure (Chaturvedi et al. 2013; Hejazi et al. 2013). Other models (WaterGAP, H08, PCR-GLOBWB), although projecting demand for non-agricultural uses, do not yet account for future changes to irrigation water requirements (Wada et al. 2016). Through the linking with the LPJmL model (Gerten et al. 2004), the IMAGE model (Stehfest et al. 2014) allows for the incorporation of the effects of irrigation water deficits over crop production as calculated in Biemans (2012, Chapter 4).

Considering that livestock water demand has an overall low share in total withdrawals (1-2%), this water user type is considered in just a few models (WaterGAP; PCR-GLOBWB; GCAM). However, as highlighted in Wada et al. (2016), livestock water demand may significantly expand in the future due to increases in livestock production resulting from population growth, and diet change as a function of growth in prosperity. When accounted for, this water demand type is calculated as the consumption per livestock head multiplied by headcount statistics typically derived from FAO data. Water use projections are driven by changes in demand for meat and dairy products induced by socioeconomic development (Hejazi et al. 2014).

Outside agriculture, water demand is generally specified in a more aggregated manner through the use of proxies for the three decomposition channels of *scale*, *intensity* and *structure*. Thus, industrial water demand is not considered through use patterns of individual industrial sectors, but rather as an aggregate explained by levels of industrial activity (scale), technological advancements (intensity) and economic development (structure). Water use follows the expansion of industrial output adjusted, however, with potential efficiency gains of more water-productive technologies and with changes of industrial production structure by assuming that, due to economic growth, the economy shifts to less water-intensive activities. Some models rely on high-level metrics as scale drivers such as GNP (Shiklomanov & Balonishnikova 2003), household consumption (PCR-GLOBWB) or electricity production (H08), whilst in others, industrial scale is measured more precisely through industrial gross value-added (WaterGAP; IMAGE) or industrial output (Shen et al. 2008; GCAM). The intensity and structural changes of industrial water use are collapsed into a single water use efficiency parameter (Shiklomanov & Balonishnikova 2003; WaterGAP; Hayashi et al. 2013) or are represented distinctly (H08; PCR-GLOBWB). A subset of the reviewed models ties water use patterns to that of electricity (H08) or energy use in general (PCR-GLOBWB; Hayashi et al. 2013; Shen et al. 2008; IMAGE). Therefore, it is assumed that changes in aggregate energy productivity are good indicators of both economic development and water efficiency gains. The authors, however, do not give any indication on why energy use patterns should be similar to those of water use.

Table 3.1 - Water demand representation in global bio-physical models

Model/Study	Spatial resolution	Agriculture		Industrial	Domestic/Municipal
		Irrigation	Livestock		
Shiklomanov & Balonishnikova (2003)	regional	Projections driven by irrigation land expansion as function of socioeconomic drivers, climatic conditions, land and water resources	n/a	UNIDO GNP-based calculations with adjustments for efficiency gains	Domestic and public-use withdrawals: withdrawals/capita saturation to developed countries' levels
WBM (Vorosmarty 2000)	0.5°	Irrigated land distribution from Döll & Siebert (2000) and WBM irrigation water intensities Projections based on Shiklomanov (1999)	n/a	Domestic and industrial water demand taken together Projections based on Shiklomanov (1999)	
Shen et al. (2008)	0.5°	No distinction between crop classes, country-level irrigation water intensities Projections driven by irrigated land expansion tied to population growth, and irrigation intensity changes	n/a	Driven by industrial output and water use efficiency improvements tied to energy efficiency gains	Driven by population and GDP/capita following the pattern of developed countries
WaterGAP (Flörke et al. 2013)	0.5°	Differentiated by 26 crop classes, irrigated areas from Portmann et al. (2010) **No projections**	Consumption per head x livestock number FAO livestock statistics	Thermoelectric: fuel type and cooling mix of power plants Manufacturing: water intensity, gross value-added and technological change	Function of population, water intensity and technological change Logistic function for municipal water intensity dependent on GDP/capita
H08 (Hanasaki et al. 2013)	0.5°	Differentiated by 11 crop classes, irrigated areas from Monfreda et al. (2008) **No projections**	n/a	Withdrawals function of electricity production, industrial water intensity (m^3/year/MWh) and annual efficiency gains	Withdrawals function of population, municipal water intensity (L/day/capita) and annual efficiency gains
PCR-GLOBWB (Wada et al. 2014)	0.5°	Differentiated by 26 crop classes, irrigated areas from Portmann et al. (2010) Paddy/non-paddy crops **No projections**	Consumption per head x livestock number FAO livestock statistics for base year	Withdrawals function of economic development (per capita GDP, electricity production, energy consumption and household consumption) and technological development	Function of total population, economic development (per capita GDP, electricity production, energy consumption and household consumption) and technological development

Model/Study	Spatial resolution	Agriculture		Industrial	Domestic/Municipal
		Irrigation	Livestock		
GCAM (Hejazi et al. 2014)	Regional and AEZ	Differentiated by 12 crop classes Irrigation water intensities from Chapagain & Hoekstra (2004) Crop output projections from Bruinsma (2009)	Consumption per head x livestock number FAO livestock statistics for base year Projections based on meat and dairy demand	Thermoelectric, primary energy production and manufacturing withdrawals. Thermoelectric withdrawals dependent on fuel type cooling mix of power production Primary energy production by energy type Manufacturing withdrawals scale up to total industrial output	Driven by population, GDP/capita, and water price; technological change (efficiency) from (Hejazi et al. 2013)
Hayashi et al. (2013)	0.25°	Differentiated by eight crop classes Own irrigation water intensities Irrigation efficiency from (Döll & Siebert 2002) Crop production projections by crop type from Kii et al. (2013)	n/a	Industrial withdrawals function of country-level industrial output of water-intensive sectors and water-use efficiency. Water-use efficiency tied to energy-use efficiency from the DNE21+ model.	Withdrawals function of GDP/capita and urban/rural withdrawals and 'access per person' calculations
IMAGE (Stehfest et al. 2014)	5 arcmin	IMAGE-LPJmL model linking Withdrawal projections from Biemans (2012)	Consumption per head x livestock number Projections adjusted for climate change	Base year manufacturing withdrawals from WaterGAP (Alcamo et al. 2003); withdrawals function of industrial gross value-added and structural change Thermoelectric withdrawals from GCAM (Davies et al. 2013); withdrawals function of energy production determined internally	Base year values from WaterGAP Withdrawals function on population, income and access to water

Two models further disaggregate industrial water demand into sub-components. WaterGAP distinguishes between abstractions for thermal power plant cooling and manufacturing uses. GCAM breaks down industrial use into thermoelectric, primary energy production and manufacturing. Thermoelectric withdrawals in all models are specified as a function of cooling technology (e.g. once-through and tower cooling) and fuel type. Projections of cooling withdrawals take into account the expansion of thermal power production but also the evolution in the mix of cooling methods. Through the addition of water demand in both electricity production and primary energy extraction, the GCAM model is capable of projecting industrial water use under different assumptions for climate change policy (Hejazi et al. 2014).

Municipal water demand is modelled in a similar way to industrial demand by distinguishing between the scale, efficiency and structural change components. The scale of water use is determined across all models by population change. Hayashi et al. (2013) and WaterGAP further distinguish between urban and rural population to capture differences in water use levels between the two groups. Also, Hayashi et al. (2013), instead of using total population figures, employ 'access-persons' values, i.e. population with access to safe water, to also tie municipal water use to the achievement of the water-access targets of the Millennium Development Goals which ended in 2015. Structural changes are induced by the evolution of GDP/capita. The relationship between water use and income levels is assessed either through regression analyses (WaterGAP; H08; GCAM; Hayashi et al. 2013) or by assuming that water demand per capita levels in developing countries converge to values observed in developed countries (Shiklomanov & Balonishnikova 2003; Shen et al. 2008). PCR-GLOBWB includes other economic development metrics in a similar way as for the specification of structural changes for industrial water demand. In some models, municipal water demand is also considered to be time-variant by including an efficiency gain parameter (intensity) into the projection exercises (WaterGAP; PCR-GLOBWB; H08; GCAM). These changes reflect an assumed tendency of household appliances to become more water-efficient over time.

As mentioned above, these biophysical models determine water demand projections without considering any feedback effect of water scarcity. With water shortages leading to the curtailing of water supply to the different water users, changes in water demand could take place at each decomposition level:

- Scale – a reduction in water demand by all users through an overall reduction in economic output and consumption

- Structure – a re-allocation of limited water resources across the different users based on different allocation methods
- Efficiency – a substitution of water resources with other production inputs (e.g. water-efficiency capital)

Although this family of models generally does not incorporate these water demand interactions, the projections obtained through these frameworks are useful in informing baselines for future water use patterns. These baselines can then be used to calibrate economic models which have the capacity to capture the different effects of water scarcity through market price signals.

Nevertheless, it should be highlighted that given the heterogeneity across these models in modelling freshwater uses, even for coordinated specifications of socioeconomic development as in the WFaS model intercomparison work (Wada et al. 2016), projections can vary significantly at both sectoral (Figure 3.1A) and regional levels (Figure 3.1B). These differences can come from the use of different datasets for base year withdrawals (2010 values in Wada et al. 2016), but also from the way economic development and population growth are translated into water demand for each user type represented. A discussion of ways in which this modelling uncertainty could be reduced is outside the scope of this thesis (this is done to some extent in Wada et al. 2016). However, it is important to acknowledge the existence of these model disagreements as these have important implications for the measurement of future water demand impairments.

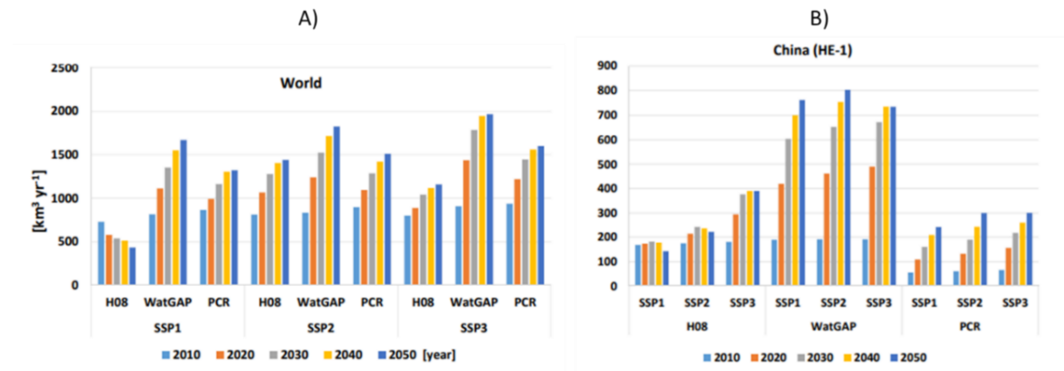


Figure 3.1 - Industrial water demand projections in WaterGAP, H08 and PCR-GLOBWB across different socioeconomic pathways

Source: Wada et al. (2016)

3.3. Economic modelling

3.3.1. Partial equilibrium models

This study has identified three partial equilibrium (PE) modelling frameworks focussing on issues related to global water use: IMPACT-Water, MAgPIE and SIMPLE-G. To date, these have focused on the use of water in relation to agricultural activities. The economic dimension of these models consists of the representation of market equilibrium in respect of agricultural commodities determined on the supply side by the cost of production and on the demand side by the demand price. The emphasis is placed on the microeconomic decisions related to the choices of production technologies. As revealed below, each model has a different way of representing water availability as a constraint to production. Water scarcity can thus lead to a re-allocation of water resources based on, inter alia, crop water productivity (IMPACT-Water), or through a substitution with other factors of production (MAgPIE, SIMPLE-G) such that total agricultural water demand equals total availability.

Overall, PE models coupled with spatial information on crop growing conditions enable the identification of scarcity "hot-spots" at high geographical resolution. However, these global-level frameworks focus on agriculture alone, whilst other user classes are regarded as exogenous water demand types driven by socioeconomic development. Thus, by fixing water demand in non-agricultural activities, trade-offs between the wider sectors based on relative water productivities cannot be assessed.

3.3.1.1. IMPACT-Water

IMPACT-Water (Cai & Rosegrant 2002) was the first model to explicitly introduce water as a constraint to crop production in a global-level PE framework. As an improvement to the initial IMPACT food multi-market model (Rosegrant et al. 1995), this modified version was used in Rosegrant et al. (2002) with the aim of analysing global food security given socioeconomic development and water availability constraints. IMPACT-Water added two components to the IMPACT base version - a spatially-detailed hydrological module (IGHM) specialised in run-off calculations (30 arc-min resolution), and a water allocation module (IWSM).

The first version of IMPACT-Water was structured around 281 food producing units (FPUs) representing aggregated geographical areas obtained as the intersection between major river basins and the national boundaries for 115 countries. Food production was detailed through 45 commodity classes (crops, livestock and processed) and was distributed across the domestic market and exports through an international trade specification. Water demand was calculated monthly for each FPU and was differentiated by four user classes – irrigation, livestock, industry and domestic.

In a first stage, unconstrained water demand was determined for each user class. Demand for irrigation water was determined spatially based on crop water requirements for optimal growth, precipitation, cropping patterns determined at a grid-cell level, and an irrigation efficiency calculated at the basin level. Livestock water demand was calculated as the multiplication of livestock production and requirements per unit of livestock commodity. Water demand for industrial purposes was determined through a linear regression of GDP per capita and time using historical water use data from Shiklomanov (1999). The time variable was added to reflect the technological gains in industrial water uses. Domestic water demand was computed as the product of population and demand per capita, whilst the latter was introduced as a function of income per capita and a water demand income elasticity. In the second stage, demand was adjusted based on water demand price elasticities specific for each user type. However, water prices were considered exogenously and were used for the scenario specification of water conservation.

The water demand-supply balance was solved monthly at the level of each FPU. Water availability was determined using the IGHM module which accounted for total FPU inflows, generated run-off, recharge of groundwater, transfers between basins and desalination. Environmental requirements in the order of 5-15% (35% for rivers with navigation) were deducted from total availability, whilst the existence of reservoirs would increase the water availability through a transfer between monthly volumes. In river basins where total unconstrained demand exceeded available supply, adjustments to the irrigation water supply were made by deducting non-crop demand volumes from total supply. Thus the water allocation method across different user classes implied treating crop production as the lowest priority user, whilst the demand outside agriculture was left unaffected by scarcity. Alternative allocation methods were stated as part of the model capabilities (de Fraiture 2007) although these were never detailed in terms of technical specifications nor were these explicitly used in the global-level model applications with a focus on water scarcity (Rosegrant et al. 2002; Nelson et al. 2010).

Irrigation and livestock water were the only endogenous demand types in the model and were driven by the total production of crops and livestock commodities. Production levels were determined based on endogenous commodity world prices which were solved such that a demand-supply equilibrium in the world market was obtained for every commodity type. In addition, crop production was constrained by water volumes made available to each crop type. Thus, in irrigation water-deficient FPUs, yields and harvested areas were changed based on model water-stress reduction coefficients. The model allocated water to different crop types through fractions calculated as a function of crop-specific profitability, water stress sensitivity and irrigation water intensity.

In the second (Rosegrant & the IMPACT Development Team 2012) and third (Robinson et al. 2015) versions of the IMPACT-WATER model some simplifications were made to the area response to water stress by integrating climate-related area impacts from DSSAT crop modelling. Also, industrial water demand in the third version was modified by specifying this as a function tracking the growth rates of manufacturing value-added and electricity production, both of which were taken from the EPPA CGE model (Chen et al. 2015) and were applied to all countries with exception of those in Africa. The third version also included improvements in data resolution with the IWSM module operating with 320 FPUs from 159 countries and 62 commodities, with the IGHM representing run-off at 0.5° resolution.

IMPACT does not include water as a standalone factor of production with a specific factor market rent. Therefore, water scarcity does not impact the overall production costs of the different water users even across food production types. Furthermore, the water allocation mechanisms to cope with water scarcity are similar for all three model versions and imply no trade-offs between agricultural and non-agricultural users. Hence, by treating agriculture as the lowest priority users, the impacts of water scarcity on agricultural output may be overstated considering that alternative water management options which prioritise food security could be possible.

As a PE model, IMPACT-Water cannot integrate by itself the macroeconomic implications of socioeconomic development relative to the economy-wide availability of capital and labour. The model specification implies an unlimited supply of these two factors at fixed prices. Therefore, when assessing the future irrigation water demand as a function of the expansion in agricultural commodity demand, this does not take into account that socioeconomic development can lead to crowding out effects of the use of some factors outside agriculture. Considering that crop production is labour-intensive, changes in labour prices induced by demand for labour in industry and services can impact the crop production costs and implicitly crop production outcomes and irrigation water demand.

To address this limitation, IMPACT-Water was linked to the GLOBE CGE model (McDonald et al. 2007) in Ringler et al. (2016) to incorporate input price changes for crop production which could not be calculated in a PE setup. This model linking aimed to capture resource interdependencies between energy, food and water under different climate change mitigation scenarios. The two models were aligned in terms of GDP and population growth. Also, the GLOBE crop prices were equalled to those in IMPACT through the introduction of an endogenous total factor productivity (TFP). A global carbon tax was considered as the main mitigation measure. This tax was introduced in the GLOBE model as an additional sales tax for fossil fuels with implications for the fossil-fuel intensive users, e.g. the chemical sector which produces fertilisers. The subsequent changes in fertiliser market prices were then reflected as changes in crop production costs in the IMPACT model.

3.3.1.2. MAgPIE

The MAgPIE model (Lotze-Campen et al. 2008), described as a "non-linear programming model with a focus on agricultural production, and land and water uses", also employs price and cost information to balance global demand and supply of agricultural products. Whilst crop demand and prices are set exogenously, the model optimises production costs of 20 cropping and three livestock activities such that a market equilibrium is obtained across 10 food-energy categories and 10 world regions. Production is calculated at a grid cell level (3° resolution and later decreased to 0.5°) and is constrained by land and water availability which is in fixed supply for both resources. Production costs are determined by capital, labour and chemicals inputs and are considered in unlimited supply using constant prices with cost information taken from the GTAP 7 database (Narayanan & Walmsley 2008). Growth in crop production is possible through the expansion of cropland and irrigation schemes implying additional output costs. In grid cells where all land and water resources are used up, yields can be improved through the adoption of yield-enhancing technologies which imply exponentially growing costs dependent on the agricultural development in every region. At the same time, yield increases on irrigated land are dependent on the use of additional blue water specified as a linear relationship.

The coupling of MAgPIE with the global hydrology-vegetation LPJmL model determines water availability for irrigation and crop yields. LPJmL calculates available water discharge for each grid cell by factoring in basin hydrology and evapotranspiration levels of natural vegetation starting from base year cropping patterns derived from Döll & Siebert (2000). In MAgPIE, water scarcity is then expressed through a water shadow price (WSP) determined spatially (Schmitz et al. 2013). This value is calculated using the dual solution of the MAgPIE model. Through this approach, the willingness to pay for increasing the supply of water in each grid-cell is revealed by relaxing the water constraints with one unit. WSP is thus equal to the production cost savings for one additional cubic metre of the water made available above the upper grid cell limit.

Consequently, grid cells not requiring all the available water have a shadow price equal to zero, whilst a positive value results in water-constrained areas. The model thus represents an evolution from the biophysical models reviewed above by introducing production-side microeconomic behaviour in grid-based water scarcity calculations.

The model is used in Schmitz et al. (2013) across nine socioeconomic development pathways in the 1995-2045 horizon to show the alleviating effects of trade liberalisation and low animal-based consumption over water scarcity incidence which is measured through WSP. Projections of demand for agricultural products are based on calculations of food demand as a function of GDP per capita and population growth. Another innovative feature of the model is the introduction of irrigation efficiency gains which follow GDP per capita levels and thus track changes in irrigation withdrawal requirements occurring with economic development.

A limitation of MAgPIE, also acknowledged by the authors, is that a positive WSP value indicating an increased cost of production due to water scarcity does not influence demand levels. Hence, WSP values obtained are higher than when demand for agricultural products decreases as a consequence of increases in market prices. Another limitation is that the model does not account for other uses outside agriculture as in the case of IMPACT-Water. Considering that water demand for industrial and municipal purposes is expected to expand notably in the areas characterised by high WSPs (South Asia and the Middle East), water availability constraints for agriculture would increase and would implicitly exacerbate the shadow price levels. Therefore, whilst the model is a powerful tool for assessing changes in water demand and their implications over water scarcity in scenarios with different demand structures of agricultural products, it cannot capture the feedback effect of scarcity on economic output as the supply of agricultural commodities always matches the specified exogenous demand.

3.3.1.3. SIMPLE-G

A recent development in the partial equilibrium modelling of water scarcity is the SIMPLE-G model (Liu et al. 2016). SIMPLE-G was conceived as a simplification to global CGE models by adopting only the crop production specification and commodity market clearing condition[3] in order to allow for a grid-based representation of production constraints coming from limited water availability. The model comprises four commodity types (crops, livestock, processed food and non-food) with their supply coming from two productive sectors (rainfed and irrigated crops). Production of the two crop varieties is specified separately at the level of each grid-cell

[3] As a PE framework, SIMPLE-G does not cover the market clearing of other factors of production (capital, labour), the income flows, nor the model closure specific to CGE models.

(0.5° resolution) and then combined as imperfect substitutes through a CES bundling. The grid-level crop output is then aggregated at a regional level (16 regions) where the market clearing takes place. International trade is specified either through frictionless integration (one single commodity world price) or through segmented markets where the regional market price enables the clearing condition.

Similarly to most CGE models, crop production functions are specified through multi-level CES input nesting. At the top level, land and non-land inputs are combined through a Cobb-Douglas assumption. Non-land inputs have one price per region and are thus supplied regionally using an elasticity of supply parameter. Land supply is specified at a grid-level and is determined by land supply elasticities and initial land rents. Water is also an explicit factor of production and is introduced at the second level of the irrigated crop production function as a perfect complement to irrigated land, i.e. an increase in irrigated land inputs determines the same percentage change to water inputs. Water supply is fixed and is specified at a sub-basin level (intersection of major river basins with national boundaries resulting in 958 sub-basins). The scarcity value of water is therefore fully reflected in the crop production costs and is determined by the equilibrium water price in each sub-basin.

The availability of water is exogenous and is calculated spatially using an updated version of the WBM hydrological model (Wisser et al. 2010). The water supply for crop production is calculated by deducting industrial and domestic water uses from total sub-basin availability. Projections of non-agricultural demand are based on population and GDP growth. Industrial demand is obtained through a GDP demand elasticity whilst domestic demand is calculated as the product of population income per capita and an income elasticity of demand. The elasticities for both industrial and domestic water demand are set at 0.2 as a middle point in the 0.1-0.3 range of values obtained by Nauges & Whittington (2009) for household income demand elasticities in developing countries. Base year industrial and domestic demand are taken from FAO AQUASTAT (FAO 2016) and are downscaled to a grid cell level based on spatially-distributed population and GDP data, although the methods or the source of the downscaled data used in the model are not revealed.

As with MAgPIE, SIMPLE-G makes important advances in reflecting local water scarcity conditions in regional crop production. Compared to MAgPIE, the model also captures the effects of scarcity on crop output by factoring in the water scarcity value. This allows the employment of the framework to compare food security impacts (output and price changes) of different scarcity adaptation measures – international trade, water use efficiency and interbasin transfers. It is worth highlighting that the latter measure can only be specified in models operating with disaggregation of water demand at river basin levels.

At the same time, SIMPLE-G faces a few limitations which are inherent to frameworks operating at such a high geographical resolution. With crop demand determined at a different spatial level than crop supply, market prices are formed at a regional level whilst technological decisions are made at a grid-level. This demand and supply implementation constrains the model to consider a single crop commodity type. A consequence of this specification is that the model cannot capture the water efficiency gains achievable through an inter-crop re-allocation of water to reflect the differences in water productivities across crop classes. With water explicitly priced in conditions of scarcity, a re-allocation could take place from low- to high-productivity crops up to the point where the marginal value product of water is equal across all crop types considered.

Another limitation relates to the way irrigation water scarcity is determined at a sub-basin level. Firstly, economic data is generally reported at a national level and methods used to downscale this can produce unreliable results (van Vuuren et al. 2007). Hence, the GDP and industrial output data used to calculate industrial water requirements at a grid-level may lead to results not reflecting real water demand levels. Secondly, industrial demand may not be accurately determined by assuming GDP as a good indicator of the spatial distribution of industrial water use. In reality, different industries have different water intensities, and water withdrawals can be concentrated in specific areas of river basins, e.g. power plants or mining sites. Thirdly, as with IMPACT-Water, by treating crop production as least priority user, the other water demand types remain unconstrained, and thus irrigation water scarcity can be overestimated.

3.3.2. General equilibrium models

Computable General Equilibrium (CGE) models have been used extensively to analyse water-related issues in relation to economic activity and food security. The growing body of literature has been acknowledged in several papers and book chapters reviewing these modelling efforts (Johansson 2005; Dudu & Chumi 2008; Dinar 2014; Calzadilla et al. 2016). There are several advantages of using CGE models over PE models. First, CGE frameworks allow for an economy-wide consistency in the allocation of resources which is important in multi-period analyses where the supply of capital and labour changes as a function of socioeconomic development. Second, CGE models include the full value chains of commodity production. Sectoral interdependencies are thus captured through the specification of intermediate demand in production technologies. In global models, the importance of international trade in economic activity could thus be captured more completely through inter-regional dependencies specified by trading pairs. Third, macroeconomic impacts of policy measures, technological changes or resource scarcity can be measured through the inclusion of metrics of aggregate output and welfare.

At the same time, CGE models also face some limitations compared to PE as outlined in Nelson et al. (2010 p.5). One of the critiques consists in the neoclassical set of assumptions typically made in global-level modelling – market equilibrium, zero economic profit, rational behaviour of producers and consumers. Also, all production and consumption decisions are based on price signals, usually described by "well-behaved" CES functional forms. Therefore, constraints in the production of a commodity need to be reflected as changes in the commodity cost structure. In contrast, partial equilibrium models allow for the consideration of non-cost biophysical restrictions specific to the sector of analysis e.g. crop production, facilitating the coupling with other model types such as land-use, hydrological or climatic models.

CGE models are also limited in their capacity to represent spatially the heterogeneity of production coming from differences in agro-ecological conditions. This limitation is due to their reliance on monetary data collected at a national level through national accounting rules. Sub-national data may be available notably for federal states but these may be structured around administrative units which do not necessarily overlap with natural boundaries e.g. river basins. Nevertheless, as outlined below, some models make use of remote-sensing data to map agricultural production into geographical units within a region (agro-ecological zones and river basins) to reflect differences in crop growing conditions.

3.3.2.1. FARM

The FARM model (Darwin et al. 1995) was the first global-level framework to introduce water as a distinct factor of production. Starting from the GTAP database, FARM comprised eight regions and 13 commodities, including three crop classes. A first application of the model was to capture the economic impacts of climate change on agriculture through the inclusion of land- and water-related adaptation measures. Land inputs in this version of FARM were differentiated in six classes based on growing season lengths given climatic conditions. Interestingly, land was considered as an input to all economic activities and not only agriculture. Acreage information per land class was determined using a GIS model and production of each of the three classes was derived from FAO data. Water was added as a factor to the production of crops, livestock and services. Water physical inputs were determined based on water usage data from a Water Resources Institute (WRI) dataset separating agricultural and non-agricultural uses. The disaggregation of agricultural water uses was made assuming an allocation of 90% to crops and 10% to permanent pasture for livestock.

As the earlier versions of the GTAP database only included labour and capital endowments, some changes were made to accommodate the value information for land and water. First, land values were deducted from capital based on factor payment information obtained from a literature review conducted by the authors. The commodity output values attributed to each land type were used as weights for the division of land payments by the multiple classes represented in the model. Second, the total value of water payments was deducted from land. Water valuation was done by taking US farm survey data for water payments and applying these to all world regions using FAO withdrawals data. Third, irrigation capital was also calculated as a share of land rents based on information revealing the extension of the growing period induced by the use irrigation. The resulting value was deducted from land and then re-attributed to capital endowments.

In Darwin et al. (1995) climate change impacts included temperature and precipitation changes calculated through global circulation models (GCM) and were implemented through alterations to land distribution by land class and water availability. Total land and water supply were exogenously specified using a run-off supply elasticity deduced from literature. Adaptation to climate change was made possible through substitution between factors of production – between land classes, and with land-water substitution considering potential increases in water supply due to climate change – but not with intermediate goods as these were introduced at the top-level of the production function through a Leontief nesting (Figure 3.2). Economic impacts were calculated for the year 1990 in comparative-static simulations. In Darwin (2004) the analysis was extended to include CO_2 fertilisation effects as an indirect effect of increasing GHG concentrations. The new simulations included elements of socioeconomic development in the 1990-2050 timeframe (capital and labour supply changes) and technological improvement (crop TFP) to capture the importance of the timing of climate change impacts.

The representation of global water use in the FARM model was undertaken at a time where data availability was a restriction for further detailing water inputs throughout the economy. Nevertheless, the model makes use of economy-wide production information to capture the competition over water resources of both agricultural and non-agricultural sectors (services), although results are reported only in relation to agriculture. The water valuation method implies that the marginal productivity of water revealed by the US irrigation water rents applies to all sectors, and to all world regions, both developed and developing. This assumption is an important deviation from reality considering the regional heterogeneity in terms of water uses and water pricing both within agricultural sectors and outside.

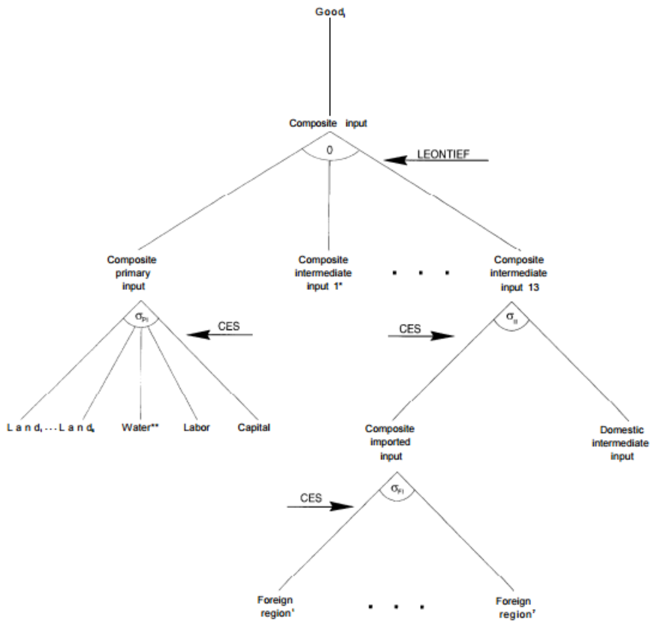


Figure 3.2 - FARM production function of water users

Source: Darwin et al. (1995)

Water scarcity in the FARM model is captured through changes in market prices of water endowments given alterations of water availability set exogenously. Therefore, the model does not allow for an expansion of water uses in water-abundant regions which could use this competitive advantage to increase the output of water-intensive commodities. Also, the behaviour of crop production in dealing with water scarcity is constrained by the lack of differentiation between irrigated and rainfed land types. Considering that technological improvement and climate change could have different yield implications for the two growing methods, the model does not allow for an adaptation based on a substitution effect between the rainfed and irrigated production.

3.3.2.2. BLS-AEZ

The Basic Linked System (BLS) CGE model coupled with the Agro-Ecological Zoning (AEZ) crop model was initially used in a number of studies to capture the relationship between socioeconomic development, climate change and land use (Rosenzweig & Parry 1994; Parry et al. 2004; Fischer et al. 2005). The coupling consisted in BLS using the arable land supply possibilities calculated by AEZ. These were determined at a grid-cell level given land suitability and profitability information to determine land use expansion coming from growth in agricultural output. AEZ was also used to calculate yield alterations due to climate change and would pass these to BLS as changes in land factor productivity.

The BLS model was structured around 35 regions, nine agricultural commodities and one additional sector aggregating all other economic activities. The model was extended in Fischer et al. (2007) to account for irrigation water requirements given socioeconomic development and climate change in the 1990-2080 horizon. Irrigated land was used as a proxy for irrigation water demand – considering the expansion of arable land, an exogenous fraction of irrigated land to total arable land derived from Bruinsma (2003) was applied to determine the arable land under irrigation. An irrigation water intensity was then calculated on a per hectare basis for every region in AEZ and then applied to irrigated land obtained in BLS in order to calculate regional requirements of beneficial irrigation water. The irrigation intensities would reflect the blue water requirements to compensate for sub-optimal soil moisture as an average across four crop classes. Total withdrawals were determined by factoring in irrigation efficiency rates which were specified to evolve exogenously over time.

Water was thus included in BLS as an implicit factor of production which entailed that, although the model allowed for the calculation of a regional water scarcity metric, water availability was not a limiting factor in crop production expansion. Also, by fixing the share of irrigated land in total land inputs, BLS would not be able to account for substitution effects between rainfed and irrigated land given potential yield differentials in both “perfect mitigation” and climate change sets of scenarios. Another limitation in the calculation of water requirements was the assumption of a representative average water coefficient applicable to all crop types. In practice, different crops have different water requirements, and thus a re-allocation of irrigated land from one type to another determines a change in water demand patterns with implications for total water requirements for crop production.

The model was also used to calculate the net benefits of climate change mitigation for agriculture under the SRES B1 emissions scenario. The results show a reduction in irrigation water requirement from mitigation leading to cost savings for irrigation supply. On the costs side, the authors estimated the cost of expanding irrigation supply by using survey data from a subset of regions for fixed and variable costs. On the benefits side, mitigation would also enable a boost in crop production increasing agricultural GDP. Whilst the benefits were calculated by BLS, the investment costs were determined starting from the additional irrigation requirements but were not reflected in the model results by deducting these from economy-wide investment.

3.3.2.3. GTAP-W1

Similarly to the FARM model, the first version of the GTAP-W (Berrittella et al. 2007) model allowed the consideration of different types of water uses outside agriculture. The model specification was an evolution of the energy-specific GTAP-E model (Burniaux & Truong 2002) and comprised 17 sectors of which four crop classes and one livestock. The calibration of the model was made using GTAP data for the year 1997 which enabled the identification of "water distribution services" (WDS) as a standalone sector. As highlighted by the authors, the inclusion in the model of WDS with a distinct production function allowed for the differentiation of water as distributed water and as a factor of production (primary resource). Thus, as a commodity, distributed water was included in the model with a separate production function and implicitly with a non-zero market price even in the absence of scarcity to reflect the costs of distribution.

Water as a factor of production was included in the production technologies of two categories of users - agriculture (crops and livestock) and WDS. The addition of water was done at the top-level nest which combined water factor inputs with the intermediate demand and the value-added composites (Figure 3.3) with a zero elasticity of substitution (EOS) assumption, a typical specification of top-level bundling in GTAP models. This Leontief specification implied that the initial sectoral water intensities of agriculture and WDS could not change through substitution effects as a function of water prices and could only be modified through exogenous factor productivity shocks. The benchmark demand of water for agriculture was determined by multiplying the green and blue water intensities obtained from Chapagain & Hoekstra (2004) with crop and livestock production statistics from FAO and did not include irrigation losses. The WDS water demand was calculated by summing up industrial and municipal withdrawals from FAO AQUASTAT.

GTAP-W1 was used in Berrittella et al. (2005) to capture the economy-wide impacts of water scarcity (GDP and welfare) and to analyse the role of international trade of "virtual water" as an alleviating factor. Two levels of scarcity were introduced in the scenario design - a mild scarcity reflecting basin-level water shortages calculated in Rosegrant et al. (2002), and an increased scarcity due to delayed policy intervention. Water deficits were manifested through a reduction in water demand across users. Interestingly, in the scenario specification, water supply in non-scarce regions was increased such that these regions could take advantage of the competitive advantage induced by water availability. However, the authors do not offer details on the drivers of this expansion.

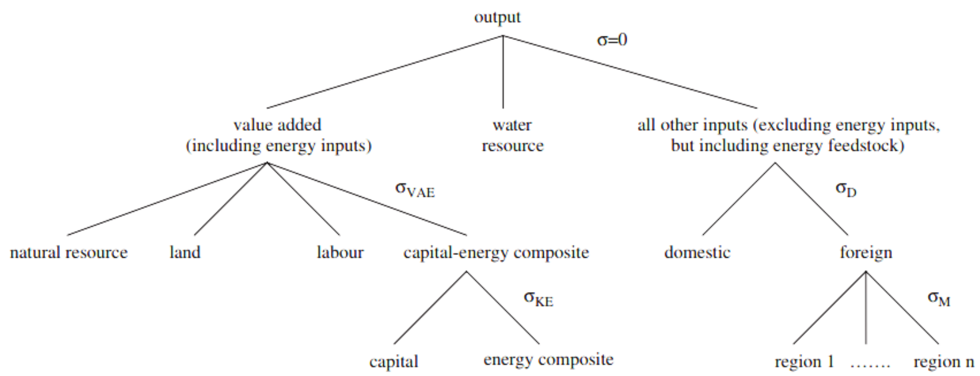


Figure 3.3 - GTAP-W1 industrial sector production process

Source: Berrittella et al. (2007)

Changes in water uses were achieved through two different methods. The first method was market-based and thus implied the introduction of water scarcity rents influencing water demand. Using this method, the price of water obtained became positive in the presence of water shortages. Implicitly, the allocation of water across users was based on differences in water productivity. The basic specification of water allocation was that of full water mobility between agricultural users but perfect immobility between agriculture and WDS. Perfect mobility in agriculture induced one single water scarcity value for crops and livestock - water endowments were re-allocated until the marginal value product became equal for all agricultural users. At the same time, WDS faced a different water value, as the water markets for the two user categories were completely separated.

For WDS, scarcity led to an increase in production costs passed through the market price of distributed water. Spill-over effects were thus induced to industrial and services sectors using distributed water, but also to households as the commodity was also part of the consumption basket. For productive sectors, water efficiency possibilities through substitution of distributed water with other inputs were limited given the GTAP-W1 Leontief nesting of the intermediate demand bundle. Furthermore, considering the insubstantial volumes of distributed water traded internationally, the growth in imports from water unconstrained regions into water-scarce regions was also low as the model considered an Armington specification for international trade through which domestic and imported varieties are imperfect substitutes. Therefore, an important driver of economy-wide water efficiency was represented by the international trade of water-intensive commodities. For households, the substitution of distributed water with other consumption goods was higher given the Constant Difference of Elasticities (CDE) demand system.

The second method used for water allocation acknowledged the difficulties in introducing market mechanisms and thus did not rely on water price signals to influence demand. Instead, a direct reduction in water uses was targeted by endogenising sectoral total factor productivity levels. With a lower productivity, production costs would increase, demand for commodities would be reduced and thus fewer water inputs would be required due to the general reduction in economic output. The authors found that the global welfare and GDP losses with the non-market mechanism were considerably higher. These results were explained by the lack of adaptation capabilities as water could not be re-allocated across users based on the water marginal productivity differences.

Although developed more than a decade ago, GTAP-W1 remains one of the few global CGE frameworks to capture the economy-wide impacts of water scarcity by determining an endogenous reduction in water demand across multiple non-agricultural sectors[4] - directly for agriculture, and indirectly through distributed water for industrial activity, services and households. These impacts were reported in Berrittella et al. (2007) in terms of GDP losses, equivalent variation and sector output changes. GTAP-W1 was further used to analyse the importance of trade liberalisation in alleviating the effects of water scarcity (Berrittella et al. 2008).

Some limitations in the model implementation can nevertheless be identified. First, the perfect immobility in water uses between agriculture and other sectors does not hold in real conditions. Although the authors argue that these uses account for different water types, in reality, irrigation and water distribution abstractions tap on the same resource base. At the same time, the treatment costs are taken into account in the WDS for the supply of distributed water and already reflect the higher quality requirements outside agriculture. Second, there is no distinction between industrial sectors in terms water dependency as the Leontief bundling of intermediate demand goods applies to all production functions. In practice, some sectors may substitute away from water uses more easily (e.g. services) than others (e.g. power production). Third, but also related to the second point, the attribution of industrial water supply to different activities needs further qualification. The industrial water volumes used from AQUASTAT statistics also bundle self-abstracting industries, of which withdrawals for power plant cooling represent a large share. Therefore, treating self-abstracting sectors separately from WDS would better reflect the gains from re-allocating resources under water scarcity conditions given

[4] The topic of economy-wide impacts of water scarcity has re-gained attention only recently through the work of Roson & Damania (2016) – see model overview below.

differences in water productivities and how water is used across self-abstracting sectors. Fourth, the model provides some insights into the amplified impacts of delayed policy intervention to cap water withdrawal. However, these do not account for the possible growth in water demand which may occur in the process. As the scenarios are comparative-static, the model does not account for socioeconomic development which increases the demand-driven scarcity. Fifth, as acknowledged by the authors, a more detailed representation of crop water use by separating irrigated and rainfed requirements would be required to capture the adaptation through increased rainfed production in conditions of reduced irrigation water supply.

3.3.2.4. GTAP-W2

The second version of GTAP-W (Calzadilla et al. 2010) was calibrated onto the base year 2001 using the GTAP 6 database. The model evolution was centred on irrigation as the largest water user. The production function of agricultural sectors was further developed to account for the different land type inputs (rainfed, irrigated and pasture). Rainfed land and an "Irrigated Land-Water" (ILW) composite were introduced as direct substitutes in the CES production technologies of the six crop classes represented, together with labour and the capital-energy bundle (Figure 3.4). The ILW composite was added as a CES specification of irrigated land and irrigation. As detailed in Calzadilla et al. (2011a), the EOS between the inputs of the two factors was calculated starting from water price elasticity values obtained from Rosegrant et al. (2002). The resulting regional values used were in the range of 0.04-0.14, specifying thus a low substitutability. Furthermore, a sensitivity analysis of EOS was conducted showing that the model results are insensitive to the variation of this parameter.

For the separate representation of arable land through the two types (rainfed and irrigated), the model database was modified using a two-stage disaggregation procedure (see Calzadilla et al. 2011). In the first step, the land rents in crop production were split into rainfed and ILW rents. This was done by using weights derived from monetary values for crop output of each of the two growing methods. The rainfed and irrigated production values were taken from the IMPACT model for the year 2000 (Rosegrant et al. 2002) and then multiplied by global crop market prices. In the second step, the resulting ILW composite value was further divided into irrigated land and irrigation equipment. The split was done based on the IMPACT data on yield differences between rainfed and irrigated land. The shadow price of irrigation was thus equalled to the additional rents obtained on irrigated land relative to rainfed land calculated on a per hectare basis. The underlying assumption was that irrigation improves land yield and that yield values on land equipped with irrigation return to those on rainfed land in the absence of irrigation. The resulting value-added of irrigation was considered by the authors to be that of irrigation equipment combined with that of water.

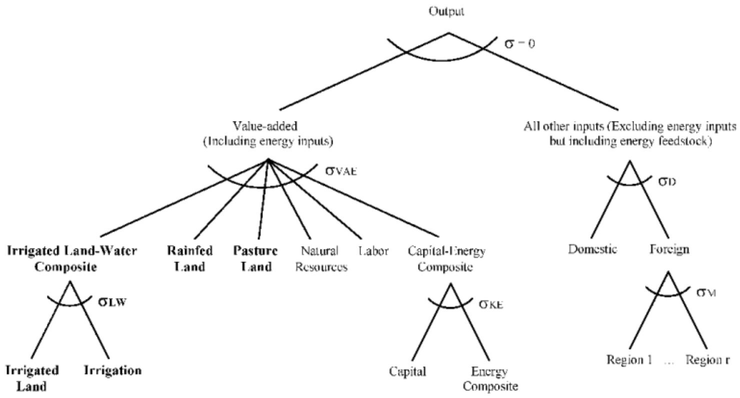


Figure 3.4 - GTAP-W2 crop production function

Source: Calzadilla et al. (2011b)

GTAP-W2 was used across a number of scenarios measuring the economic impacts of changes in irrigation water supply. Calzadilla et al. (2010) determine the GDP and welfare impacts for the year 2025 of the two alternative water management scenarios used in the IMPACT model in Rosegrant et al. (2002) – "water crisis" and "sustainable water". Similarly to GTAP-W1, the model was used in a comparative-static setting, however, the economic database was updated to 2025 using forecasted values for labour productivity and stocks of labour and capital from an intertemporal CGE model. The future supply and allocation of irrigation and those of the two arable land types were calculated based on acreage and land yield values obtained from the IMPACT scenarios.

In Calzadilla et al. (2011b) and Calzadilla et al. (2013), the model was used to determine the incidence of climate change over welfare, crop output and irrigation water use for 2020 and 2050. Climate-driven changes in irrigation supply were determined through supply elasticities relative to river-flow, with elasticity values obtained from Darwin et al. (1995). Implicitly, in regions with increased precipitation levels irrigation supply was expanded and, conversely, decreased in regions with reduced annual precipitation. At the same time, the model simulation included yield changes induced by alterations to crop growing conditions (climatic and CO_2 fertilisation), implemented as changes to factor productivity of the land-related inputs (ILW and rainfed land). The obtained results for changes in total irrigation water use thus captured two effects – changes in the overall supply of irrigation and the re-allocation of irrigation water use across crop classes given relative yield changes.

The model comprises a set of limitations when dealing with the economy-wide impacts of water scarcity. As opposed to the first version from Berrittella et al. (2007), the model only focuses on water uses in crop production, thus excluding all the other sectors such as livestock and industry. The GDP impacts obtained in Calzadilla et al. (2010) are limited to the direct and spill-over effects of constrained crop production and could thus be underestimated considering that water shortages could also impact other sectors. Therefore, a distinction in how water is qualified between the two model versions is in order. In GTAP-W1 water refers to endowments which have a zero price when scarcity is absent, whereas in GTAP-W2 the value of water is included in that of irrigation which is supplied subject to water availability scenarios.

Next, changes in irrigation supply are only occurring in the model through biophysical changes (river-flow) or through prescriptive scenarios (water management leading to zero-cost irrigation efficiency gains). Thus this exogenous specification of irrigation supply does not allow for any market-driven increase in irrigation water use, notably in regions with abundant resources. The fixed irrigation supply is in contradiction with the significant increases in irrigation water uses observed even in the recent past as a consequence of higher land productivity obtained with irrigation and growth in crop commodity demand.

The non-separation of irrigated and rainfed production is also a limitation in establishing the adaptation of crop production to water scarcity through a shift towards rainfed production. As argued in Taheripour et al. (2013a), in extreme conditions such as a generalised drought, irrigated production could be turned off completely. In GTAP-W2 the disabling of irrigation is not possible without the collapse of the entire crop output due to the CES specification of the value-added nest.

Last, irrigation as equipment is treated as a homogeneous factor, i.e. one single price per region, and thus is not allocated across crop types based on the relative crop water intensities (m^3 / $ of output) but based on the differences in irrigation productivity ($ of irrigation value-added / $ of output). This implies that for any given irrigation supply, the irrigation price reflects the marginal productivity of irrigation which is equal across all irrigated crops. However, the corresponding water price expressed per m^3 of irrigation water is not the same across crop classes, as indicated by the baseline values calculated in Calzadilla et al. (2011a) – see Figure 3.5. Therefore, in conditions of reduced irrigation supply as a consequence of water scarcity, the implicit distribution of water uses through the re-allocation of irrigation endowments does not reflect the shadow scarcity value of water but the shadow price of irrigation equipment. A case in point is the irrigation price obtained for the JPK region (Japan and Korea) which is considerably higher than that of other regions reflecting the importance of irrigation equipment in crop production in spite of the region dealing with low or no water deficits.

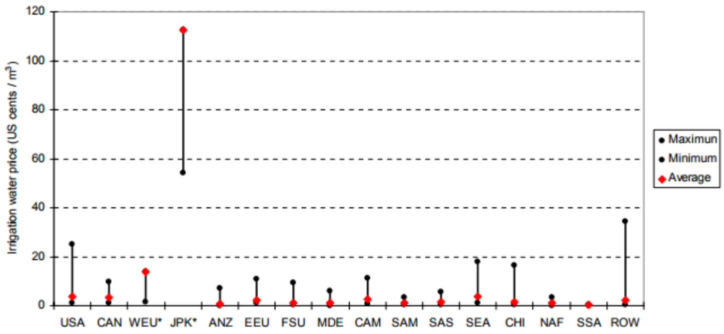


Figure 3.5 - Irrigation water price across regions and crops in the GTAP-W2 baseline

Source: Calzadilla et al. (2011a)

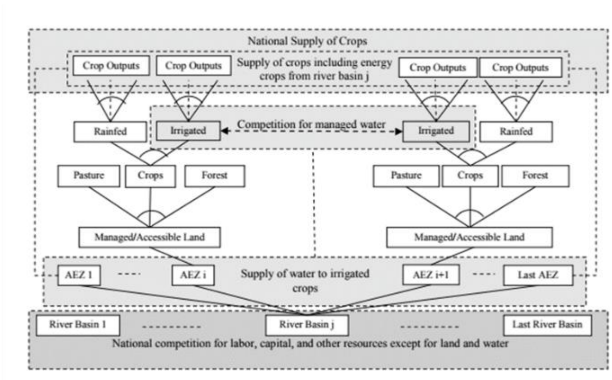
3.3.2.5. GTAP-BIO-W

Taheripour et al. (2013b) further extended the representation of water use in crop production through GTAP-BIO-W. The model was a development of the biofuel version of the GTAP-E model, GTAP-BIO. The advantage of using GTAP-BIO as a starting point consisted in the model's capacity to represent land heterogeneity through agro-ecological zoning (AEZ). Thus crop production was detailed across up to 18 AEZ by region, accounting thus for a wide range of yield differences resulting from soil suitability and climatic conditions. Available land in each AEZ was allocated across three land types (crop, pasture and forest) using a constant elasticity of transformation (CET) functional form. Relevant to the model applications, GTAP-BIO introduced new biofuel commodities through separate production functions which require feedstock inputs coming from food crops (corn, sugar cane and processed oils). Therefore, in this specification, biofuel production competes with other sectors using crops as inputs such as food processing.

In GTAP-BIO-W, rainfed and irrigated crop production were further detailed through distinct nested CES functions. Total output by crop class was split into the two growing methods using production volume information from the SAGE database (Monfreda et al. 2008) and by assuming identical cost structures for non-land inputs. For irrigated production, irrigation water was added as a separate factor of production by deducting the initial value from land inputs through the same accounting principles as in GTAP-W2 – higher yields on irrigated land are reflected in higher land rents which are then fully attributed to the use of irrigation. Hence, land rents were calculated by using yield and acreage information from Portmann et al. (2010) aggregated for each AEZ within every region. By using this disaggregation method, the obtained water endowments largely represent the irrigation capital as in the case of GTAP-W2.

Water inputs were considered to be river basin (RB) specific, with each region having up to 20 RBs. Thus competition between crop classes for land and that for water resources was implemented at different levels. Allocation of land resources took places at the AEZ level, whilst water allocation was done at the RB-level with transfers between AEZ belonging to the same RB being allowed. Where one river basin was shared between two or more GTAP-BIO-W macro-regions, water resources were split into different segments and cross-boundary transfers were not permitted.

A)



B)

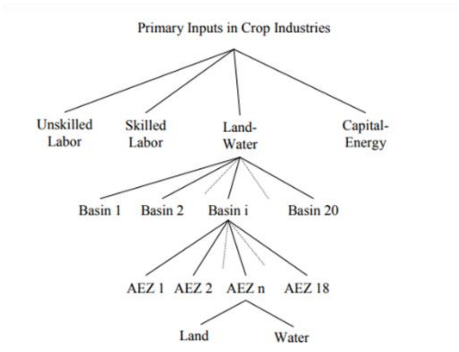


Figure 3.6 - GTAP-BIO-W crop production modelling

Source: Taheripour et al. (2013a)

The crop production functions replicate the GTAP-E specification, similarly to GTAP-W2, with a few alterations in the structure of primary inputs demand. Rainfed land was added as an input only to rainfed production whilst irrigated land was combined with water inputs for irrigated production. Hence, in GTAP-BIO-W the substitution between the two land types did not occur directly within the production function, but indirectly when the irrigated and rainfed varieties of one crop type were combined at a regional level (Figure 3.6A). The outputs of the two varieties were bundled using a CES function, assuming thus imperfect substitution between the two varieties. For irrigated crop production, land and water inputs were nested for every RB-AEZ possible combination within a given region (Figure 3.6B) by specifying a non-zero EOS which varies from one region to another. However, the authors do not elaborate on the methods used to calculate these elasticities.

Building on the land allocation mechanism from GTAP-BIO, the model allows for some degree of flexibility in attributing the land resources at three different levels – crop and non-crop activities, across crops, and between rainfed and irrigated production. Therefore, the availability of irrigated land could change by using price signals through these three different margins. For water, the allocation is less flexible as total water availability is set exogenously for each RB. Therefore water supply could only be distributed across activities of the different AEZ within an RB.

Although the model makes important advances in illustrating the impacts of water scarcity down to a river basin level in connection with a heterogeneous representation of land endowments, it shares many of the limitations found for GTAP-W2. The main shortcoming consists in restricting the analyses to crop production. Given the geographical resolution of the model, as in the case of the SIMPLE-G model reviewed in Section 3.3.1.3, the introduction of other sectors competing over water resources is difficult due to lack of data regarding the spatial distribution of economic activities and their use of water. Such a task is facilitated for crop production by the advancements in remote sensing methods and water crop modelling. However, determining the location of complex economic activities and their supply chain on a global map by using national accounts as a starting point is prone to delivering unreliable results. Furthermore, the method by which water is represented in crop sectors in GTAP-BIO-W is unsuitable for other sectors as this comprises both the added value of water and that of irrigation equipment. For other activities, the value of water could be revealed differently, if at all. For instance, municipal water users employ distributed water which has production costs different to those in irrigation. At the same time, self-abstracting activities such as thermal power generation may have a licence to withdraw but with the costs of water extraction hidden behind other inputs. Therefore, to extend the model to other sectors, it would be required to a) distinguish between irrigation equipment and physical water inputs in crop production, b) represent physical water uses outside crop production at a river basin level and c) allow for competition over physical quantities between agricultural and non-agricultural users. Whilst tasks a) and c) were addressed, for instance, in GTAP-W1 through a separate consideration of water scarcity rents (task a) and the allocation of water across different crop classes (task c); task b) may be currently impossible given the lack of spatially-detailed water use data.

3.3.2.6. EPPA

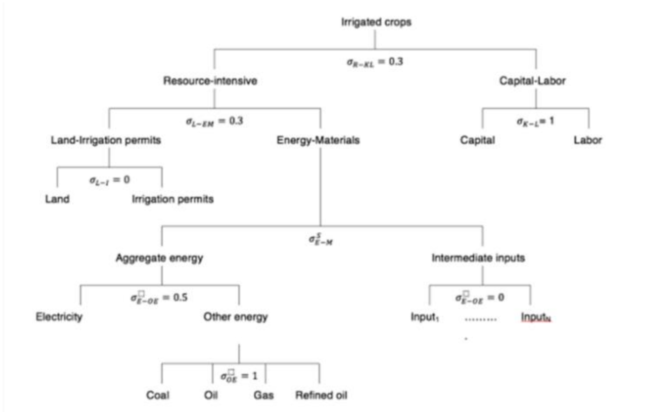
Water was introduced in the land-use EPPA model to capture the constraints of water availability in implementing climate-related policy through bioenergy production (Winchester et al. 2016). The model development followed the structuring from Taheripour et al. (2013) of crop production through an explicit differentiation between rainfed and irrigated production implemented at a river basin level. The novelty of the model comes from the consideration of land conversion possibilities. Whilst the generic model version is capable of changing land-use allocation across six land classes (crop land, managed forest land, natural forest land, managed grassland, and other land), in Winchester et al. (2016) crop land was further disaggregated into the rainfed and irrigated types with each having a distinct supply specification.

The EPPA model explicitly represents land conversion costs through a CES nesting of labour, capital and intermediate inputs in the same way as productive sectors are typically specified in GTAP-based models. Also, the nesting structure sets the substitution elasticities such that the land additivity property is preserved i.e. conversion of one hectare of one land type leads to a hectare of another land type. This property is not maintained in models using a CET function to allocate land resources across different land-use types, as discussed in van der Mensbrugghe & Peters (2016). In the EPPA model, the land additivity is ensured by specifying land inputs at the top level of the land conversion function with a Leontief nesting with all other inputs (Gurgel et al. 2007).

In the water version of the model, crop land use is mobile across rainfed and irrigated production. For irrigated crop production, land is combined with an "irrigation permits" good through a Leontief bundling (Figure 3.7A). Irrigation permits are supplied by a standalone production function (Figure 3.7B) and therefore the availability of permits determined by market prices limits the extent to which land for irrigation is employed. The base year value of irrigation is calculated in a similar way to Taheripour et al. (2013a) by relying on yield differences between rainfed and irrigated land. However, the value of additional production on irrigated land on a per hectare basis is attributed entirely to irrigation permits, and thus the initial cost structure of irrigated crops is split into two production functions – that of irrigated crops per se and that of irrigation permits– with each employing capital, labour and intermediate inputs.

The production of permits is calibrated by taking into account the costs of conversion but also the maximum irrigation potential given water availability in each production area (irrigation response units – IRUs). A permit supply elasticity is estimated through the consideration of region-specific irrigation supply curves determined by water storage and irrigation efficiency costs, with data taken from the IGSM-WRS integrated assessment model (Strzepek et al. 2012). This supply elasticity is then implemented in the permit production function through the introduction of an "irrigation-specific resource" substitutable with the composite of all other inputs (see Figure 3.7B). The initial value of this resource and that of the EOS are determined to replicate the irrigation price elasticity of supply by using a method from Rutherford (2002). The maximum irrigation potential is included in the permit production function through the addition of "irrigation certificates" inputs at the top-level Leontief nest. The total number of certificates is determined by the land acreage that can be irrigated at the maximum irrigation efficiency given the total volume of water available for irrigation in each IRU. The exogenous specification of certificates supply enables the model to run different water availability scenarios and can reveal the water scarcity value through the market price of irrigation certificates when these are undersupplied.

A)



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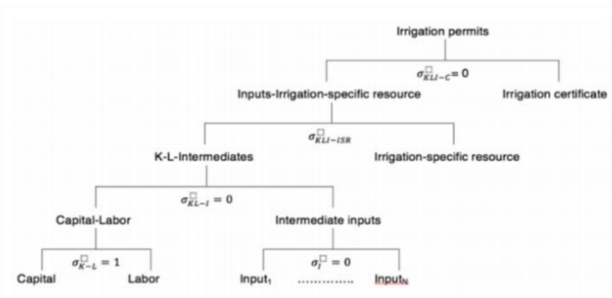

Figure 3.7 - EPPA irrigated crop production function

Source: Winchester et al. (2016)

In Winchester et al. (2016), EPPA is used to capture the competition over land resources of food resulting from socioeconomic development and climate-change mitigation policy through bioenergy production in the 2010-2050 timeframe. Whilst food crops are specified to be produced on both rainfed and irrigated land, bioenergy technologies are assumed to use cropland without irrigation. Interestingly, the authors obtain only marginal differences in land use results between model specifications with or without water constraints. Nevertheless, limited water availability resulted in a 10% increase in the welfare losses associated with the implementation of climate policy (CO_2 taxation).

A major advancement of EPPA compared to the CGE models reviewed above is the model's ability to endogenise the expansion of regional water demand using market signals. At the same, the model contains a few limitations in analysing the economic impacts of water scarcity. On the one hand, food crops are represented as one single commodity, and thus the model does not enable water productivity gains obtainable through the re-allocation of irrigation across crop classes. Furthermore, even with more than one food crops class, the re-allocation of irrigation permits would still not capture the differences between crop types in terms of water productivity as irrigation permits are introduced as a homogenous good – the water intensity of one permit is implicitly the same across all uses. Therefore, the model is unable to capture the fact that whilst the same irrigation technology could be used across all crop types, the water requirements per unit of irrigation can vary according to the evapotranspiration level of each crop type. On the other hand, as for most other global models reviewed here, the relationship between socioeconomic development and water scarcity is represented only through food demand increases and thus only covers agricultural water demand. Although Winchester et al. (2016) envisage a scenario of a 20% reduction in irrigation water availability in order to allow for more water to be used by other sectors, this method is prescriptive and does not capture the wider effects of competition over water resources between multiple water user types.

3.3.2.7. ICES-W

The ICES-W specification detailed in Ponce et al. (2016) shared many similarities to GTAP-W2, in that it used GTAP-E as a starting point but also in terms of crop production representation. Cropland was split into the irrigated and rainfed types which were then used as inputs in one production function per crop class. Irrigation was also introduced as a distinct factor of production defined as "irrigation capital". As a modification to GTAP-W2, the model crop production was specified to isolate the substitution between arable land types from all other factors by combining land-related inputs into a "Land-IrLand" bundle (Figure 3.8) using a non-zero EOS. Irrigated land and irrigation capital were further separated into a distinct nest from rainfed land, again using a positive EOS.

The database used was a disaggregation of GTAP8 for 2007. As opposed to GTAP-W2, rents on irrigated capital were deducted from capital and not from land endowments. To do this, the authors compiled the data from several studies covering 1200 irrigation projects around the world to determine region-specific investment requirements on a per hectare basis. Total irrigation investment was obtained by combining investment averages with the total area equipped for irrigation in each region using information from Siebert et al. (2010). Rents paid for irrigated capital were then calculated by applying an irrigation-specific rate of return to total irrigation investment. The resulting irrigation capital rents amount to about 2% of capital rents globally for the year 2007. Another difference from GTAP-W2 was that arable land was split into rainfed and irrigated land using area shares of the two land types and not through weights calculated with production monetary values. Whilst ICES-W provides an alternative to the valuation of irrigation in crop production, the same limitations exposed for GTAP-W2 are applicable – the model focus on crop production only, the combined irrigated and rainfed production, the allocation of irrigation treated homogenously and not reflecting the differences in water productivity between crops.

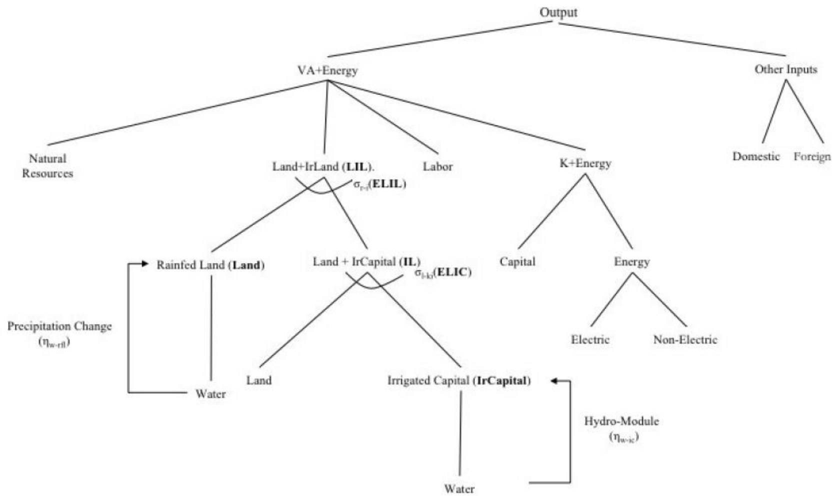

Figure 3.8 - ICES-W crop production function

Source: Ponce et al. (2016)

ICES-W is used in Ponce et al. (2016) to determine the economy-wide impact of changes in water availability due to climate change. These changes were translated into the model through comparative-static runs as productivity shocks applied to rainfed land and irrigation capital. Productivity changes on rainfed land were equalled to the changes in precipitation levels, whereas productivity on irrigation capital was linked to changes in river flow. The calculation of river flows was done through a simplified hydrological module soft-linked to ICES-W. In contrast to GTAP-W2, a reduction in water availability, instead of changing the supply of irrigation endowments, leads to changes on the demand side by decreasing irrigation productivity.

3.3.2.8. GTAP-RD

The model used in Roson & Damania (2016) to measure the macroeconomic impacts of water scarcity was specified as a standard GTAP model[5] (Hertel & Tsigas 1997) with water included as an implicit input to production. Sectoral water demand was linked to sectoral output through sector-specific water use coefficients. The coefficients were derived from multiple sources – WIOD (Dietzenbacher et al. 2013), WASSERMed (Mielke et al. 2010), Mekonnen & Hoekstra (2010) –, and considered to be time-variant through the assumption that users become more water-efficient over time.

In Roson & Damania (2016) and World Bank (2016), the model is employed to project regional water uses under different socioeconomic pathways using the SSP framework (van Vuuren et al. 2014). To determine future water deficits, the water demand projections are compared to water availability values derived from hydrological simulations of the GCAM model. To determine the economic impacts of water scarcity, water demand in regions with water deficits is reduced using two alternative methods – a uniform reduction in water use across sectors and a differentiated reduction based on sectoral water productivity. With water not included as a standalone factor of production, water demand is reduced through shocks in total factor productivities (TFPs) affecting sectoral output. Through the first water use reduction method, the same TFP change is applied to all sectors, whereas through the second, TFPs are reduced more in water-intensive sectors and can also increase in some water-productive sectors. The results indicate that regional GDP is significantly affected by the uniform water use reduction – up to 14% in the Middle East. These negative impacts are however alleviated when water can be re-allocated towards water-efficient activities, with even positive GDP impacts in certain water-scarce regions.

Through the consideration of the relationship between water use and socioeconomic development, GTAP-RD is an important step forward regarding the measurement of economy-wide impacts of demand-driven water scarcity in the future. However, the model would require more detail in the specification of water demand by individual productive sectors. Through the employment of water use coefficients, water demand patterns are considered in a "top-down" manner. This approach does not allow for any water scarcity adaptation mechanisms other than the prescriptive re-allocation of water based on relative water productivities set exogenously, leading possibly to an over-estimation of economic impacts. Other adaptation measures outside the implied reduction in economic output of water-intensive sectors could include the

[5] The model does not have a name. In this thesis it is referred to as GTAP-RD

substitution between rainfed and irrigated crops or the substitution of water with other inputs within production processes – in GTAP-RD all sectors implicitly include water as a perfect complement to other inputs. Furthermore, the model is based on a sectoral aggregation of two sectors with very different water productivities through the bundling of water distribution with power generation in one 'utilities' sector. This lack of detail limits the differentiated adaptation to regional water deficits of these two major water users.

3.3.2.9. Discussion

The CGE modelling review indicates that there is some diversity in the manner water availability is included as a constraint to economic activity. Table 3.2 condenses the relevant specifications in relation to water modelling work analysed above. As in the case of partial equilibrium models, most CGE frameworks have attempted to capture the impacts of limited water availability over crop production, with just two instances (FARM and GTAP-W1) endogenously accounting for competition over water resources by other sectors - services and water distribution services respectively.

For agriculture-centric models, the inclusion of water in crop sectors was also implemented using different approaches depending on how water was qualified as an input to production. One reason for this diversity arises from the fact that water payments in irrigation are not captured by global economic datasets used in water CGE modelling such as GTAP. The prevalent approach is to deduct the base year value of water inputs from the value of other factors of production – land (FARM, GTAP-W2, GTAP-BIO-W, EPPA) or capital (ICES-W). The values obtained and qualified by some of the authors as "irrigation water inputs" represent to the largest extent additional rents paid for access to the irrigation facility and hence cannot be unambiguously attributed to water as a scarce natural resource. In practice, water scarcity is rarely acknowledged through the prevention of unsustainable withdrawals, and therefore generally the base year irrigation water values obtained in these models represent the shadow value of irrigation equipment and the corresponding conveyance infrastructure.

The unclear terminology surrounding irrigation water use has important implications for the interpretation of model scenarios and results. When water scarcity is increased on the supply-side by decreasing the availability of the irrigation water factor (Calzadilla et al. 2013; Liu, Thomas W. Hertel, et al. 2016), it is, in fact, the availability of irrigation infrastructure that is reduced and not necessarily that of water. Implicitly, changes in the allocation of irrigation water driven by price signals reflect the differences in irrigation infrastructure productivity. With different irrigation water intensities across crop types (m^3 of irrigation water/$ of irrigation value-added) the control over total withdrawals cannot be obtained by setting the level of irrigation supply exogenously. A reduction in the supply of irrigation would determine the re-allocation of irrigation towards the crops which are more irrigation-productive (higher $ output / $ of irrigation value-added). If these crops happen to be more water-intensive, then this re-allocation leads to an increase in overall withdrawals, opposite to the intended effect.

Another approach to include water in production technologies (GTAP-W1) was to leave the cost structure in the baseline unchanged and to include scarcity rents in alternative water availability scenarios. In this case, the underlying assumption is that scarcity rents are not reflected in the base year economic data and that these become positive when water availability is reduced. As opposed to the first approach, payment of scarcity rents are attributed to the volumetric use of water and, therefore, the scarcity scenarios in GTAP-W1 lead to an absolute cap over withdrawals.

The two approaches are *not* however mutually exclusive. As discussed in Chapter 2, the irrigation water payments could include both the irrigation supply costs attributed to the irrigation infrastructure and the scarcity value when a withdrawal limit is considered. Therefore, current water models could be improved to account for water and irrigation infrastructure uses separately. The first attempt in this respect was made in the EPPA model through the inclusion of the “irrigation permits” production function which covers the irrigation supply costs of labour and capital, but also the water scarcity rents of the “irrigation certificates”. Nevertheless, as highlighted in Section 3.3.2.6, the attribution of certificates to a homogenous irrigation permits good and not to the crop production function, does not allow for a differentiation between crop classes in terms of water intensities.

Another improvement could be made in the case of models deriving the value of irrigation from land endowments (GTAP-W2 and GTAP-BIO-W). These models originally use information of yield differentials between rainfed and irrigated land by splitting land payments in irrigated crops into irrigation and irrigable land. Therefore it is assumed that in the absence of irrigation, yields on irrigable land equal those on rainfed land within the region under consideration. This could prove to be a crude approximation. For instance, in the arid areas of some regions, it is irrigation that can make crop production possible. Without irrigation water to compensate for chronic soil water deficiencies, yields in these areas would not return to the rainfed values of more water abundant areas within the same region, but would likely be much lower or would collapse altogether. Therefore, when accounting for the shadow value of irrigation, a more localised impact of not using irrigation needs to be factored in. Crop models calculating yields by considering local climatic and natural soil moisture conditions could thus provide more insight into changes in crop performance in the absence of irrigation water.

Scenarios for water shortages in global CGE modelling have approached imbalances induced by both sides of the scarcity equation. On the supply side, the availability of water-related inputs was influenced by changes in run-off due to climate change (FARM, GTAP-W1, GTAP-W2) or by the evolution of uses not considered endogenously in the modelling framework[6] (industrial and municipal water for GTAP-BIO-W). On the demand side, scarcity was affected by socioeconomic development (GTAP-RD), food demand expansion in particular (FARM, BLS, GTAP-W2, EPPA), irrigation efficiency changes and yield impacts of climate change with impacts over irrigation water intensities.

Thus, model simulations can further be grouped into those determining economic impacts of projected water scarcity under current economic conditions (GTAP-W1, GTAP-BIO-W, ICES-W) and those incorporating socioeconomic development to account for the timing of water scarcity incidence (FARM, GTAP-W2, EPPA, GTAP-RD). Except for GTAP-RD, models considering socioeconomic development are focused on crop production and therefore demand-induced water scarcity is driven mainly by future changes in food demand. Food output in these models is assessed in relation to a single "business-as-usual" future and thus the uncertainty regarding economic and population growth is not taken into account.

Furthermore, to track the importance of socioeconomic development for water withdrawals, CGE models would need to allow for an endogenous change in total water demand so that water-abundant regions could further make use of their resources. Except for the EPPA model which enables the expansion of irrigation through market price signals, this is not currently possible as the supply of water-related inputs is set exogenously at a regional or river basin level in all models reviewed.

Regarding the capacity of current models to include adaptation to water scarcity, most advances were made for crop sectors by enabling a separated representation of irrigated and rainfed production. For the other sectors, when non-irrigation water demand is considered, adaptation is limited due to the under-specification of water uses in production technologies. A case in point is GTAP-RD where major users are bundled in one productive sector and all economic activities are considered to have a zero substitutability of water inputs.

[6] Whilst this can be considered a demand side constraint, in the model scenarios this translates into a reduction in irrigation supply for crops.

Table 3.2 – Overview of water scarcity representation in global CGE models

Model	Water user sectors	Water representation	Irrigated/Rain fed crop distinction	Water scarcity value	Water scarcity drivers		Socioeconomic development
					Supply-side	Demand-side	
FARM (Darwin 2004)	Crops (3) Livestock (1) Services (1)	As endowment derived from land	No	Implicit	Run-off changes through climate change	Food consumption per capita	GDP and population, TFP 1990-2050
BLS (Fischer et al. 2007)	Arable land	Through irrigation water requirement coefficients	No	Implicit	None	Food demand Changes in soil moisture	IIASA A2r food demand projections
GTAP-W1 (Berrittella et al. 2005)	Crops (4) Livestock(1) WDS (1)	Water scarcity rents Distributed water sector	No	Explicit through water scarcity rents	Changes in supply from IMPACT data Run-off changes through climate change		No
GTAP-W2 (Calzadilla et al. 2011a)	Crops (6)	As endowment derived from land	Partial – irrigated and rainfed land	Implicit	Run-off changes through climate change	Food demand Irrigation efficiency gains Yield changes from climate change	IMPACT food demand in 2020, 2025, 2050
EPPA (Winchester et al. 2016)	Irrigation permits	Irrigation-specific endowment	Yes	Explicit through irrigation certificates	Irrigation water availability scenario	Food demand (direct) Bioenergy demand (indirect)	EPPA BaU 2010-2050, CO_2 taxation policy
GTAP-BIO-W (Liu et al. 2014)	Crops(8)	As endowment derived from land detailed at river basin level	Yes	Implicit	Changes in irrigation supply due to other uses	Irrigation efficiency gains	No
ICES-W (Ponce et al. 2016)	Crops(7)	As endowment derived from land External irrigation sector	Partial – irrigated and rainfed land	Implicit		Irrigation productivity losses due to climate change	No
GTAP-RD (Roson & Damania 2016)	GTAP sectors	Through sectoral water intensity coefficients	No	Implicit		Growth in economic output	GDP growth (SSP1, SSP3)

3.4. Knowledge gap and case for further model development

In spite of an increasing number of models attempting to capture the importance of a finite availability of water resources to economic activities, the assessment of economy-wide impacts of demand-driven water scarcity remains limited. This is determined by a lack of a rigorous integration of key features related to the evolution of water demand and to the feedback mechanisms of production and consumption to cope with water deficits. Table 3.3 lists these features and maps their occurrence in the models reviewed in this chapter.

Table 3.3 - Specification of key water scarcity features in global water scarcity assessments

Feature/ Scenarios	Relevance	Biophysical models	PE models			GE models							
			IMPACT	MAgPIE	SIMPLE-G	FARM	BLS	GTAP-W1	GTAP-W2	GTAP-BIO-W	EPPA	ICES-W	GTAP - RD
1. Socio-economic development	Future state of water scarcity	Y	Y	P		P	P		P		P		Y
2. Climate change incidence on water demand	Changes in water demand levels and structure	P	Y				Y		Y			P	
3. Endogenous non-agricultural water uses	Inter-sectoral trade-offs					Y		Y					
4. Water scarcity value	Allocation based on relative water productivity differences			Y	Y			Y			P		
5. Rainfed/ irrigated crop production	Water scarcity adaptation in agriculture		Y		Y				P	Y	Y	P	

Note: Y=Yes, P=Partial

With the expectation of increases in water demand to significantly impact water scarcity levels across wide geographic regions, it is important to (1) factor in the drivers behind the evolution of water uses. The connection between socioeconomic development and water demand is thus an essential component in understanding the future state of scarcity. (2) Climate change impacts on water demand could also prove to be substantial notably in agriculture as its incidence could change crop growing conditions and crop water productivity. Next, under excessive demand relative to a limited water supply, a re-allocation of water resources needs to be decided either based on market-based mechanisms or prescriptively, e.g. through fixed sectoral quotas. (3) Accounting for the water scarcity impacts across economic sectors and households would thus require an endogenous specification of water demand across all users, both inside and outside agriculture. (4) The explicit representation of water scarcity rents applicable to all water users would enable the allocation of water resources based on differences in water productivity. Finally, given the dominant role of irrigation in overall withdrawals, (5) a more advanced specification of crop production through the differentiation between rainfed and irrigated growing methods would be important in order to capture the adaptation to water scarcity in crop production through substitution of growing methods.

Biophysical models, excelling at representing the water resource availability at a fine geographical level, have also made advancements in the understanding of water use patterns by breaking down withdrawals into several user categories. Furthermore, the water demand relationships embedded have revealed the importance of socioeconomic development over the state of future water scarcity by tracking the expansion in water uses in connection with income and population growth. Nevertheless, these models cannot capture the feedback effects of water deficits on economic activities and households.

In terms of economic modelling, most work has focused so far on the issue of water scarcity in agriculture. There is a solid motivation for a detailed representation of water uses in relation to crop production as irrigation has been the main driver of water withdrawals in many water-scarce regions. However, as these regions continue to grow both economically and demographically, the role of other user types is expected to become increasingly important. Therefore, these models only partially reflect the economic impacts of water scarcity as socioeconomic development has usually been captured through the expansion of food demand with implications for irrigation water requirements, and not from other perspectives, e.g. industrial output, electricity production.

Competition over water resources coming from outside agriculture could lead to trade-offs between wider economic sectors, and the size and sectoral incidence of these trade-offs would depend on the resource allocation rules which need to be more thoroughly explored. In crop-focused models, both PE and CGE, other water demand types, when considered (IMPACT-Water, GTAP-BIO-W), were treated exogenously and were used to determine the water availability to irrigation. The allocation of scarce water resources was made with the underlying assumption of agriculture being the least important water user. For PE modelling, this is an inherent limitation as the analyses can only be focused on one sector and not the entire economy.

If fact, CGE models have the capacity to capture water uses across all sectors and to include allocation mechanisms under water scarcity. However, only three models have included non-crop water users (FARM, GTAP-W1, GTAP-RD) in their framework and have enabled some form of water re-allocation across wider economic sectors by using market price signals. The first two frameworks are by now dated and suffer from limitations as discussed in Sections 3.3.2.1 and 3.3.2.3. Also, these models have not been used to tackle the issue of demand-driven water scarcity through the lens of socioeconomic development outside agriculture (with impacts on industrial and municipal water demand) and that of climate change. In the past decade, most model development has focused on determining the water scarcity impacts on crop production. Only in the recent study of World Bank (2016), using GTAP-RD, the topic of macroeconomic impacts of future water deficits was revived. However, the low level of sectoral detail of water use dynamics remains an important obstacle in capturing the inherent adaptation mechanism of economic systems to water scarcity.

It can be thus concluded that an important advancement in the economy-wide modelling of water scarcity could be made through the integration under one general equilibrium framework of the five key features outlined above. This could be done by incorporating the state-of-the-art of crop production specification in CGE models and by expanding the sector-specific representation of water uses to other economic activities.

3.5. Conclusions

Considering the risks associated with water scarcity, there is now a growing attention given to the economic modelling of global water uses. The different efforts have all made significant advances in capturing the importance of water to economic activity. CGE models have proved to be promising tools in understanding the economy-wide implications of limited water availability through the accounting of overall factor allocation and the possibility to consider multiple water management options covering all water users. However, the capabilities of the different frameworks could be improved and could be better integrated to allow for a more detailed assessment of the impacts of future water deficits.

Going back to the three essential points for economy-wide modelling of water scarcity, through the review in this chapter, it can be concluded that:

i) **The representation of the relationship between the economy and water use** was undertaken to a large extent in biophysical modelling with a focus on water scarcity metrics. For global economic models, most work has been dedicated to capturing the link between crop production and irrigation water uses. The inclusion of non-crop sectors as water users has so far been limited, being done either through a "top-down" specification of water as an implicit factor of production (GTAP-RD) or through an aggregated view of non-agricultural water uses (GTAP-W1).

ii) **The construction of water demand projections in a world with limited water availability** was also considered by several biophysical models. In economic models, water demand projections as a function of socioeconomic development have been largely considered through the angle of changes in food demand, overlooking all other drivers. Only the recent work using GTAP-RD considers the relationship between economic growth and regional water demand across different development futures.

iii) **The inclusion of demand-driven water scarcity as a determinant in the allocation of water resources and in the economy-wide production and consumption choices**. Most economic modelling of water scarcity has focused on the supply-side of water scarcity, e.g. changes in water availability through climate change, with some elements of changes in demand patterns in addition to those of an expanding food system, e.g. yields, irrigation water efficiency improvements. In general, current CGE models do not consider the pressure on the resource base coming from expected growth in activity of non-crop sectors. Furthermore, the consideration of alternative water management options is underexplored, either by focusing on water allocation across crops only (most models) or by the use of prescriptive mechanisms (GTAP-RD). Economy-wide water allocation using endogenous scarcity price signals is thus absent in the current literature.

This chapter has thus revealed the opportunity for further model development in determining the state and the economic implications of future demand-driven water scarcity. The next chapter introduces an improved CGE framework (RESCU-Water) to address the current limitations of modelling efforts. The model specification addresses the need of integrating the key features outlined in Table 3.3 and further expands the current state-of-the-art regarding water use representation in the economy-wide modelling of water scarcity at a global level.

Chapter 4. Economy-wide modelling of freshwater uses for water scarcity analyses

4.1. Advancing the current modelling state of the art

The literature review in the previous chapter has revealed the opportunity for further research to explore the impacts of demand-driven water scarcity, both inside and outside crop production, through an extension of current assessment capabilities. Therefore, one of the main contributions of this thesis consists of the further development of global water modelling with the aim of assessing the economy-wide implications of the imbalances between an expanding water demand and limited water supply.

These imbalances are assessed through the evolution of water demand as a function of socioeconomic development and climate change. Socioeconomic development could not only increase the demand for agricultural products with implications for irrigation water requirements (Alexandratos & Bruinsma 2012) but also lead to significant growth in industrial and municipal water uses (Marchal et al. 2011). At the same time, climate change could determine alterations to blue water demand notably in crop production. The induced changes in yields, soil moisture and evapotranspiration levels could significantly influence irrigation water productivities and implicitly total irrigation water requirements (Elliott et al. 2014).

Thus, the research questions to be addressed relate to both the evolution of water demand in the coming decades and the economic impacts of demand-driven water scarcity under climate change:

1. What is the future pressure on freshwater resources coming from irrigation water requirements with socioeconomic development? Considering that demand for agricultural products is expected to increase significantly, will this translate into important increases in irrigation water demand? Will there be significant variations across alternative socioeconomic development pathways?
2. How will mounting concentrations of GHGs impact the water demand in irrigated crops? What are the dominant factors affecting crop water productivity?
3. What are the economy-wide and food security impacts of future demand-driven water scarcity under different climate change scenarios? To what extent the re-allocation of freshwater based on differences in user water productivity can be an alleviating

measure? Will climate change further amplify these impacts through alterations of water demand patterns for crop production?

The first two set of questions refer strictly to water use in crop production. These are motivated by the crucial role of irrigation over total water withdrawals and implicitly over the future state of water scarcity. Potentially small changes in irrigation water requirements can have a significant effect on the water availability for other sectors. Constructing a multi-period baseline for the pressure exerted by crop production over water resources is thus essential for any further assessment of the economy-wide impacts of water deficits. The uncertainties related to this baseline need to be thoroughly explored by considering multiple socioeconomic and climate change scenarios.

The analyses are conducted using a global dynamic-recursive CGE framework, the Resources CGE UCL Water (RESCU-Water) model, and build on the modelling work undertaken previously and detailed in the previous chapter. As in all other CGE models focusing on water scarcity, an emphasis is given to agriculture through an advanced specification of irrigated and rainfed crop production. At the same time, several important improvements are brought to the current CGE state-of-the-art. The RESCU-Water model thus addresses the limitations discussed in Section 3.3.2.9 related to the water use representation in irrigated crop production, namely:

- Irrigation infrastructure and water are treated as distinct factors of production to enable a separate accounting of water scarcity rents.
- The allocation of water across irrigated crops is done according to the productivity of crops in relation to water and not to that of irrigation equipment.
- Irrigation supply is endogenised to allow for an expansion of water use in the absence of water scarcity.
- The accounting of irrigation value added is improved by using more advanced crop modelling information on the importance of irrigation to crop performance.

Water demand is endogenised for all users through the introduction of water as an explicit input to production for all economic sectors and to household consumption. The consideration of sector-specific uses requires a further qualification of user types. RESCU-Water distinguishes between self-abstracting sectors employing water as an endowment and users supplied with water through distribution services. This distinction enables a differentiated adaptation to water shortages across households and the various economic sectors.

Water scarcity is considered by capturing the effects of competition between users in regions where unconstrained demand exceeds sustainable supply. Bearing in mind that full market-based mechanisms are difficult to implement, the re-allocation of scarce water resources is implemented using a mix of market- and non-market principles. Market-based allocation relies on water scarcity rents, whilst the non-market methods imply more fragmented water uses. The differences between methods reveal the impacts of using water in ways which do not entirely acknowledge the differences in water productivity between users. The impacts of scarcity under different allocation regimes are determined at several levels – from a sectoral perspective through changes in output, economy-wide through impacts on GDP and from a social perspective through impacts on welfare and food security.

Referring to Table 3.3, the RESCU-Water model covers all the key features argued for at the end of the last chapter. (1) Socioeconomic development is considered in relation to all user types through the construction of an unconstrained water use baseline. This baseline takes into account the scale, structural and efficiency changes occurring for the different user classes. In addition, the irrigation water requirements calculated as part of the answer to the first research question are determined based on an economy-wide consistency over the availability of labour and capital given the different socioeconomic pathways. (2) Climate change impacts on water demand are considered in relation to irrigation water and are central to the second research question. The impacts accounted for are broader than those previously and are derived from recent global crop modelling efforts. (3) All sectors have an endogenous water demand and can substitute away from water inputs in conditions of water scarcity determining thus a sector-specific adaptation to the economy-wide water deficits. (4) Water scarcity rents are explicitly represented and influence the allocation process of limited water resources. (5) The adaptation in crop production to water scarcity is enabled through the separation of rainfed and irrigated production.

The model simulations are run in the 2004-2050 time horizon. The description of the RESCU-Water model is provided in the next sections. The model is calibrated using base year water uses which are determined through the extension of the economic database with water accounts. The water accounting methods and also the valuation of irrigation as a water-related input are explained in Chapter 5. The three subsequent chapters use the model to answer the individual research questions.

4.2. CGE modelling overview

4.2.1. Background

CGE models rely on the Walrasian Equilibrium theory in which an economy is defined as being in general equilibrium when the demand and supply in all of its markets are equal. This state is enabled by adjustments in prices of all commodities and factors of production determining the way resources are allocated across the economy. The existence of such an equilibrium point as described by Walras (Walras 1899) was demonstrated by Arrow & Debreu (1954). The computability of this point was introduced in Harberger (1962) for a two-sector economy, whilst for multiple industries, this was made possible through a numerical algorithm introduced by Scarf (1969).

As argued in Devarajan & Robinson (2013), CGE models have several attributes which make them suitable for the analysis of policies with large-scale impacts. As applied models, they allow for the introduction of specific institutional or market configurations which can be subject to policy variation. CGE models are "deep structural" as these comprise a specification of different representative agents (industries, households, government and investment), the agent behaviour and the agent interactions in the commodity and factor markets through price signals. In contrast, partial equilibrium models cannot take into account the general changes in relative prices of large-scale policies as these do not have a view on aggregate factor supply nor on the clearing of all markets.

CGE models have both strengths and limitations which are inherent to the standard theory behind them (Borges 1986). The most important strengths invoked are the microeconomic foundations, the internal consistency and the high level of disaggregation of economic activity. The main critiques brought to this modelling approach concern the difficulty in conveying the results to non-specialised audiences and the neo-classical set of assumptions regarding market conditions.

Microeconomic principles are explicitly embedded by describing all agents as optimisers and therefore it is this set of behaviours that drive the solution to general equilibrium. Households are utility maximising subject to their budget constraint. Their utility is generally depicted through a standard functional form (e.g. Cobb-Douglas) and is specified through demand equations embedding the utility maximising behaviour. Firms are cost minimising, with constant return to scale production and zero economic profit, however, these perfect market competition assumptions can be relaxed through the specification of different market configurations (see, for instance, Willenbockel 1994). The optimising behaviour can be static with agents having myopic expectations regarding future consumption and profits (static-comparative or dynamic-recursive models), or inter-temporal through perfect foresight (inter-temporal dynamic models).

Next, the models are internally consistent in that all economic agents and their interdependencies are taken into account. These interdependencies are captured through monetary transactions occurring in between producers, consumers and the foreign sector as detailed through national accounting. Thus, it can also be inferred that CGE models capture the circular flow of income. By including the links between agents, model simulations account for impacts in all markets through direct and indirect feedback effects. In global modelling, the introduction of international trade also allows for the consideration of implications for foreign markets.

Finally, the disaggregation of the economy into multiple individual markets enables the assessment of sectoral impacts and economy-wide structural changes. As opposed to fixed-coefficient input-output analyses which are oblivious to price signals, technological choices and sectoral output in CGE models are influenced by changes in relative prices leading to substitution effects. The tracking of general price changes also enables the consideration of income effects through welfare measures such as Equivalent Variation.

An important limitation comes from the theoretical character of CGE models. The specification of functional forms is generally not empirically validated as in the case of econometric models which require extensive and often non-available time series data. A part of parameters are calibrated by using a single-year structure of the economy that is assumed to be in equilibrium, whilst another part (income, price and substitution elasticities) are either picked to fit standard functional forms (e.g. Cobb-Douglas) or are derived from independent literature. This calibration process limits the application of CGE models to “what-if” types of analyses rather than forecasting exercises.

CGE models usually have a complex structure described through a system of non-linear equations that requires them to be solved through numerical methods. This hampers the tracking of causality chains and has led to a “black-box” critique of this modelling framework. Nevertheless, the use in policy analysis of stylised models with a reduced number of relationships which can also be solved analytically has helped address the concerns related to the theoretical robustness of larger models (Devarajan & Robinson 2013).

Furthermore, although cost minimisation and utility maximisation are widely accepted behaviours among economists, these are components of the neoclassical theory relying on full agent rationality and perfect market conditions. Neo-classical thinking and the underlying *homo economicus* are increasingly contested by newer branches of economics and in fields outside economics which include non-market considerations (e.g. the bounded rationality adopted in behavioural economics).

That model results do not reflect the gradual changes from one state of equilibrium to another. As an example given in Harberger (1962), under the assumption of perfect factor mobility, changes in taxation of capital in one industry do not lead to a disequilibrium in capital markets through differentiated rates of returns on capital between industries. Instead, rates of return across sectors are equalised to reflect the new state of equilibrium. Therefore, CGE model simulations show the long-term impacts on resource allocation, production and consumption induced by changes to the model exogenous variables.

Although facing some limitations, CGE models have grown to become a standard tool for policy analysis (Dixon & Jorgenson 2013) and are also increasingly used in the field of sustainable development through energy-economy-environment modelling. The initial applications of CGE models referred to taxation and international trade (Shoven & Whalley 1984) and the relationship between energy prices and economic growth (Hudson & Jorgenson 1978; Manne & Preckel 1985). The analyses were limited to a single economy or a small number of countries. As the availability of multi-regional coherent data was a limitation, global economic modelling emerged later and was facilitated by the commencement of trade negotiations under the Uruguay Round at the end of the 1980s (van der Mensbrugghe 2013). The creation of the Global Trade Analysis Project (GTAP) in 1993 enabled the acceleration of global CGE analysis related to trade and agricultural policy through the compilation of a global economic database to be used with a publicly available CGE framework – the standard GTAP model (Hertel & Tsigas 1997) specified under the bespoke programming language GEMPACK.

With the advent of the IPCC assessment reports, CGE also became a tool for global environmental policy analysis. The modelling advancements in this regard consisted in the integration of environmental satellite data into the model data but also in the specification of production functions and factor supply to better represent the constraints of the biophysical environment in which economic activities take place. The standard GTAP model was thus extended to cover the many issues related the impacts of climate change and climate policy e.g. GTAP-E (Burniaux & Truong 2002) focused on the importance of energy in production functions, the land-use models GTAP-AEZ (Hertel et al. 2009) and MAGNET (Woltjer et al. 2014), the GTAP-BIO family focused on biofuel policy (Birur et al. 2008). Another strand of work used CGE models to compute the implications of climate policy on wider sustainability metrics (Carraro et al. 2013). As presented at length in the previous chapter, water scarcity has also become an increasingly important topic in global CGE modelling.

4.2.2. CGE workflow

The workflow of CGE static models is composed of three stages – data collection, model calibration and comparative analysis (Figure 4.1). The first stage regards the collection of data which describes the structure of the economy in terms of production and consumption choices of the benchmark equilibrium. The resulting dataset is structured as a balanced Social Accounting Matrix (SAM) which captures all the annual monetary flows occurring within the economy under consideration. SAMs use as starting points monetary input-output tables typically available through national accounts. These are then extended to include information on income and expenditure of final demand agents, trade and balance of payments. Global databases consist of a collection of SAMs which are further detailed on bilateral international trade flows and transport margins.

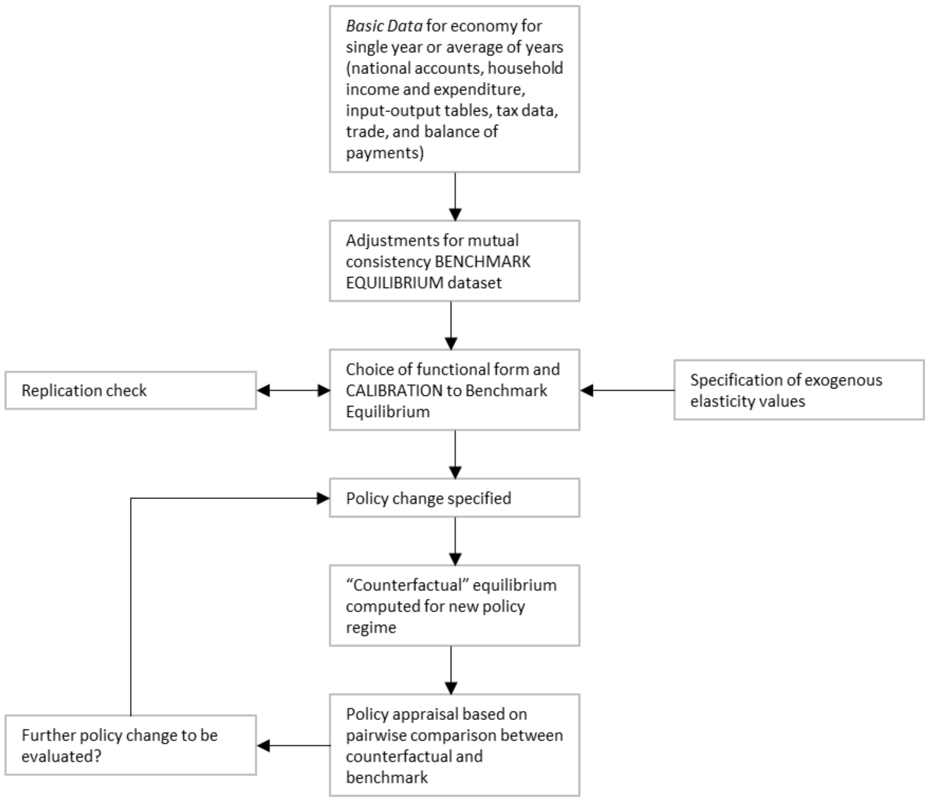

Figure 4.1 - Workflow of CGE models

Source: adapted from Shoven & Whalley (1984)

In the second stage, the production and consumption functions are calibrated starting from the benchmark dataset. As generally production functions are specified through CES functional forms, the calibration consists in the calculation of share and scale parameters starting from an exogenous elasticity of substitution. The calibration process is checked through a replication run of the model which needs to reproduce the structure of the economy without any intervention. Additional homogeneity tests can be run to also check the integrity of the model specification.

Dynamic-recursive models also need to align economic growth to external data. Therefore an intermediate stage is dedicated to the construction of a multi-annual baseline. The baseline is usually obtained by endogenising factor productivity levels such that annual exogenous GDP values are achieved in the model solution. The baseline also needs to take into account changes in the availability of factors of production, namely labour and capital depending on demographic change and investment respectively.

The last stage consists in the simulation of policy intervention through a shock to one or several exogenous variables. A shock can imply, for instance, a change in taxation of certain commodities as in the case of carbon taxes, an improvement in factor productivity as for energy efficiency gains or a reduction in factor availability as done in the simulation of water scarcity. Generally, the results are reported as changes to the baseline. These are also typically tested for robustness through sensitivity analyses of key elasticities.

4.3. RESCU-Water model outline

4.3.1. Model overview

The RESCU-Water model is built as global recursive-dynamic CGE framework. It is written in full algebraic form developed under the General Algebraic Modeling System (GAMS) and is solved using a Constrained Nonlinear System formulation (CNS). The model comprises 20 world regions which are linked through international trade and foreign capital flows. Production is structured around 31 activities and 22 demand commodities. The regional and sectoral base year data is an aggregation of the GTAP9-Power database for the year 2004 (Peters 2016) modified to map rainfed and irrigated crop production as distinct economic activities.

The model core specification shares many of the traits found in standard GTAP based models by the adoption the following assumptions:

- Perfect competition - each productive sector is represented by one regional firm which is acting as a cost minimising price taker. Production technologies are introduced through nested Constant Elasticity of Substitution (CES) functional forms which allow for a more thorough specification of substitution possibilities between factors of production and intermediate demand commodities. Sectoral output is also calibrated for constant returns to scale.

- Utility maximisation - each region has one representative household which maximises utility subject to the household budget constraint. The model adopts a Linear Expenditure System (LES) functional form which implies a calibration to include a subsistence component of the consumption of each demand commodity.
- Clearing of factor and commodity markets – all commodities and factors are fully employed. The corresponding market prices are adjusted such that demand is equal to supply in every time period.
- Homogeneity in prices and quantities – demand and price functional forms are chosen and calibrated such that the model is homogeneous of degree zero in prices i.e. changes in quantities are determined only by changes in relative prices, and homogeneous of degree one in quantities e.g. a doubling of supply of factors of production leads to a doubling of overall output.
- Armington assumption for international trade – domestic and foreign varieties are considered imperfect substitutes (Armington 1969). The model thus enables the substitution between the two varieties using a CES function with a finite elasticity. The foreign variety is further composed of imports differentiated by source region allowing for an inter-regional substitution.
- Imperfect substitution between domestic supply and exports **–** given changes in relative prices in the domestic and world market, productive sectors allocate the supply through a Constant Elasticity of Transformation (CET) function. This specification is used to capture the non-homogeneity of output destined to the two markets and the adjustments that need to be made in the production processes in order to shift production from one variety to the other.
- Investment-driven model closure - household saving propensity adjusts such that total savings (household, government and foreign) equal a target investment level. For simplicity, international capital flows are fixed and labour is immobile across regions (no migration).

4.3.2. Freshwater use modelling

RESCU-Water adds a set of features aimed at improving the analysis capabilities of economy-wide water uses. Water is thus introduced as an explicit factor of production for a number of economic activities through the employment of an economy-wide water accounting framework.

For the representation of water demand in irrigation, the model comprises an advanced representation of crop production. Rainfed and irrigated production activities of the eight crop classes represented are defined as separate functions with each using a specific type of arable land – rainfed land and irrigable land respectively. In line with other global CGE water models (GTAP-W, GTAP-BIO-W, ICES-W), irrigation as a facility (equipment and infrastructure) is added as a distinct factor of production. This input separation is done by using an improved accounting method which acknowledged the production losses when irrigation is disabled (see Chapter 5). The supply of irrigation is endogenised through a logistic function which follows market price signals. This specification enables the calculation of irrigation water requirements using the RESCU-Water framework in scenarios considering the effects of socioeconomic development, technological improvements and climate change over crop output.

For water uses in other sectors, the model distinguishes between the two possible denotations of water as an input to economic activities – as an *endowment* which is withdrawn from the natural environment by self-abstracting sectors and as a *commodity* which is supplied through water utilities (Figure 4.2). Water as a commodity is also split into *industrial water* and *municipal water* to reflect the differences in quality and implicitly the different production costs, the two having different economic values on a per cubic metre basis.

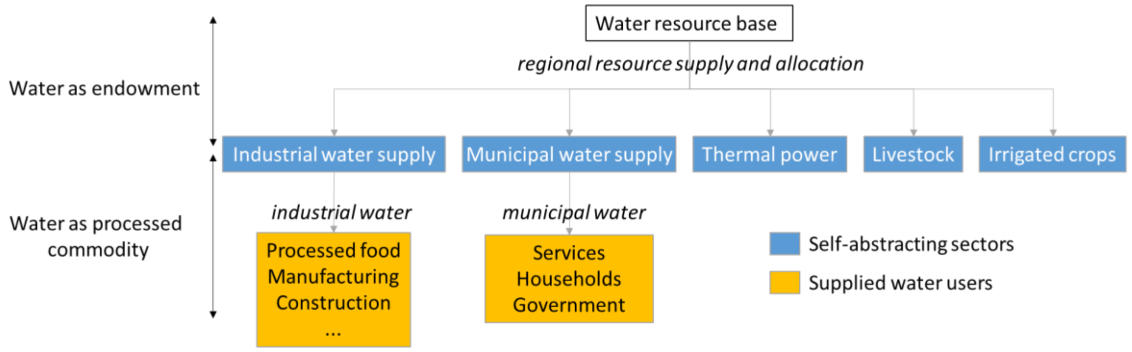

Figure 4.2 - Water classification in the RESCU-Water model

This classification method is important in model simulations which acknowledge the existence of water deficits. Without scarcity, water as an endowment has a zero price to reflect the absence of scarcity rents, and thus, does not influence the technological and consumption choices made by users. Nevertheless, under these conditions, the water commodity employed by industries, services and households does have a market value as this reflects the economic costs of treatment, conveyance and sewerage.

A positive price for water as endowment is obtained when total regional water demand is constrained to match a sustainable supply target. The corresponding rents reflect the shadow price of water as a scarce natural resource. This price increase impacts self-abstracting sectors for which water is considered to be a critical input, and thus scarcity rents are added entirely to their production costs. Scarcity rents are also passed to the supplied users (municipal and industrial) through increases in market prices of water as a commodity.

Supplied users can substitute water commodity inputs with other inputs of production or consumption, endogenously increasing their water efficiencies. Nevertheless, industries that are considered to be water-intensive (e.g. manufacturing, mining, chemicals) have a further specification of industrial water inputs into their production function. Water inputs in these sectors are separated and have a low degree of substitution with non-water inputs. This specification enables the model to account for differences between supplied users in terms of adaptability to scarcity, with some sectors being more flexible than others.

RESCU-Water also adds a level of detail regarding the impacts of water scarcity on the electricity sector. The use of the disaggregated GTAP9-Power allows for a separation between thermal and non-thermal electricity technologies which are distinctly represented in the RESCU-Water framework. Thermal power is considered to be a self-abstractor with a high-dependency on water availability for cooling purposes, whereas water inputs for the non-thermal variety are less critical being substitutable with other inputs. Therefore, the model implements an advanced adaptation mechanism to water deficits in electricity production through a differentiation of impacts between the two technological groups.

4.4. RESCU-Water algebraic formulation

4.4.1. Indices and variable notations

A number of sets are employed to condense the model algebraic specification to a manageable range of equation and variable blocks. To a large extent, the LINKAGE model equations (as described in van der Mensbrugghe 2011) were used as a reference in the RESCU-Water model development, and therefore, the variable notation is similar. An outline of the indices used is found in Table 4.1, whilst the list of variables and their corresponding equations is included in Table 4.2.

Regions

All regional variables have an *r* index which, for brevity, is implicit in most equations below. The use of the *rn* region subset is necessary to exclude the numéraire region from the equation block implementing the global Walras' Law. Another region subset *dr* is employed to group the developed regions in the computation of the model numéraire price *P* which is calculated as the aggregated export price of manufacturing commodities of these regions.

Commodities and productive sectors

The dimensions of traded commodities *k* and productive sectors *i* are equal due to the one-to-one specification for sectors and commodities[7]. Traded commodities *k* are bundled in demand commodities *cons* when different varieties of the same commodity category are produced – rainfed and irrigated for crop classes, thermal and non-thermal for power production.

Subsets of demand commodities *cons* are introduced for the isolation of manufacturing sectors *manu* in the numéraire price calculation, for the calculation of subsistence levels of *LEScons* commodities entering the LES household demand functions and the identification of commodities *tr* contributing to international transportation.

A few subsets of productive sectors are used in the differentiated specification of production functions – *irc* for irrigated crops, *rfc* for rainfed crops, *sai* for non-crop self-abstracting sectors, *ind* for water-intensive industries and *ser* for municipal water users.

Table 4.1 - Indices/sets employed in the RESCU-Water model

Index/set	Dimension	Alias	Description
r	20	rr, s, d	Regions
rn	19	Rrn	All regions minus numéraire region
numreg	1		Numéraire region {USA}
dr(r)	6		Developed regions {AUZ, NEA, NEU, NOA, SEU, USA}
f	2		Non-household final demand agents {GOV, INV}
i	31	ii	Productive sectors
wdk(i)	8		Water dependent industrial sectors

[7] In the standard GTAP model specification, investment is considered a productive sector, hence the dimension of *i* in the original GTAP data has an increment of one relative to that of *k.* The RESCU-Water model treats investment as a final demand sector in a similar way to households and government.

Index/set	Dimension	Alias	Description
wik(i)	23		Water flexible sectors
k	31	kk	Traded commodities
crops(i)	16		Crop productive sectors subset
rfc(crops)	8		Rainfed crops subset
irc(crops)	8		Irrigated crops subset
noncrops(i)	15		Non-crop productive sectors subset
sai(i)	4		Non-crop self-abstracting sectors {Livestock, Thermal power, Industrial water supply, Municipal water supply}
ind(i)	8		Water-intensive industries {Non-thermal power, Agriculture other, Processed foods, Energy, Manufacturing, Chemicals, Paper, Mining}
ser(i)	4		Municipal water users {Municipal Water, Construction, Transport, Other services}
cons	22		demand commodities
nwc(cons)	21		Intermediate demand subset excluding industrial water
LEScons(cons)	21		LES demand commodities
manu(cons)	1		Manufacturing commodity subset
tr(cons)	1		International transportation commodity subset
factor	6	fact	Endowments {Labour, Capital, Pasture, RfLand, IrrLand, Irrigation, Water}
iwl (fact)	3		Irrigated production specific factor subset {Irrigation, Water, IrrLand }
kl (fact)	2	clb	Capital-labour subset
ltype(fact)	2		Arable land types {RfLand, Irrland)
t	47		Time index {2004*2050}

Table 4.2 - RESCU-Water model variables and corresponding equations

Variable	Description	Representative equation(s)
Quantities		
XP(r,i)	Output of sector *i*	(4.25)
ND(r,i)	Demand of top-level intermediate bundle by sector *i*	(4.2)
ND2(r,ind)	Demand of second-level intermediate bundle by water-intensive sector *ind*	(4.21)
VA(r,i)	Value-added bundle demand by sector *i*	(4.1)
KL(r,i)	Capital-labour bundle demand by sector *i*	(4.5)
LND(r,i)	Land-related bundle demand by sector *i*	(4.6)
XF(r,fact,i)	Demand of factor *fact* by sector *i*	(4.8),(4.10),(4.14),(4.16),(4.18)
XC(r,cons)	Supply of demand commodity *cons*	(4.34)
ES(r,cons)	Exports of demand commodity *cons*	(4.35)
XD(r,cons)	Domestic supply of demand commodity *cons*	(4.28)
XAp(r,cons,i)	Sector *i* demand of Armington composite of demand commodity *cons*	(4.12),(4.20),(4.23)
XAc(r,cons)	Household demand of Armington composite of demand commodity *cons*	(4.45)
XAf(r,f,cons)	Demand of Armington composite of demand commodity *cons* by final demand agent *f*	(4.46)
XA(r,cons)	Total demand of Armington composite of demand commodity cons in region *r*	(4.66)
XMT(r,cons)	Total imports of demand commodity *cons* in region *r*	(4.27)
XM(s,d,cons)	Imports from source region *s* to destination region *d* of demand commodity *cons*	(4.30)
WTF(s,d,cons)	Biletaral trade flows of demand commodity *cons*	(4.36)
YH(r)	Household income in region *r*	(4.48)

Variable	Description	Representative equation(s)
Yd(r)	Household disposable income in region *r*	(4.49)
SH(r)	Household savings in region *r*	(4.52)
Yc(r)	Household disposable income in region *r* allocated to consumption	(4.51)
YG(r)	Government income in region *r*	(4.53)
TarY(r)	Government income from import tariffs	(4.54)
S(r,f)	Savings of final demand agent *f* - government and investment (foreign savings)	(4.56),(4.59)
FD(r,f)	Aggregate demand of final demand agent f	(4.55),(4.57)
WXMg	Global supply of international transport	(4.40)
AXMg(r)	Regional international transport supply	(4.41)
XMg(r,i)	Contribution of sector *i* to the regional supply of international transport	(4.43)
Kstock(r)	End-of-period capital stock in region *r*	(4.74)
DeprY(r)	Depreciation in region *r*	(4.50)
FS(r,fact)	Factor supply in region *r*	(4.62),(4.63),(4.64)
Aland(r)	Arable land supply in region *r*	(4.61)

Prices

PP(r,i)	Produce price with output tax in sector *i*	(4.4)
PX(r,i)	Net producer price in sector *i*	(4.3),(4.17)
PND(r,i)	Price of top-level intermediate bundle demand in sector *i*	(4.13),(4.22)
PND2(r,i)	Price of second-level intermediate bundle demand in sector *i*	(4.24)
PVA(r,i)	Price of value-added bundle demand in sector *i*	(4.7),(4.15),(4.19)
PKL(r,i)	Price of capital-labour bundle demand in sector *i*	(4.9)
PLND(r,i)	Price of land-related bundle demand in sector *i*	(4.11)
PF(r,fact)	Market price of factor *fact*	(4.65)
PC(r,cons)	Market price of demand commodity *cons*	(4.26)

Variable	Description	Representative equation(s)
PE(r,cons)	Pre-FOB price of exports of demand commodity *cons*	(4.33)
WPE(s,d,cons)	FOB price of exports of demand commodity *cons*	(4.37)
WPM(s,d,cons)	CIF price of imports of demand commodity *cons*	(4.38)
PD(r,cons)	Market price of domestic demand commodity *cons*	(4.32)
PA(r,cons)	Market price of Armington composite of demand commodity cons in region *r*	(4.29)
PMT(r,cons)	Market price of imported demand commodity *cons* in region *r*	(4.31)
PM(s,d,cons)	Price of imports from source region *s* to destination region *d* of demand commodity *cons*	(4.39)
PFD(r,f)	Composite price of aggregate demand of final demand agent f	(4.47)
WPMg	Price index of international transport	(4.42)
APMg(r)	Regional price of international transport supply	(4.44)
PABS(r)	Price index of aggregate domestic absorption in region r	(4.70)
P	Numéraire price	(4.68)
PINDEX(r)	Consumer price index in region *r*	(4.69)
PAland(r)	Price of arable land in region *r*	(4.60)

Macro-economic aggregates

GDPMP(r)	Nominal GDP at market prices in region *r*	(4.71)
RGDPMP(r)	Real GDP at market prices in region *s*	(4.72)
InvSh(r)	Investment share of real GDP	(4.59)

4.4.2. Model equations

4.4.2.1. Productive sectors

To account for the different water use profiles of productive sectors, the model specifies production technologies for five typologies: irrigated crops, rainfed crops, non-crop self-abstracting sectors (livestock, thermal power, industrial water supply and municipal water supply), water-intensive industrial sectors (supplied with industrial water) and services sectors (supplied with municipal water). The differences between these consist in the way factors of production and intermediate inputs are nested to capture the sector-specific substitution possibilities. This distinction is done notably in relation to the use of water both as an endowment and as a commodity (through the industrial and municipal water varieties).

Irrigated crop production

Irrigated crop production XP_{irc} is composed of a Leontief top-level nesting between the value added bundle *VA* and the intermediate composite *ND* (Figure 4.3). Equation (4.1) and (4.2) define the demand levels of *VA* and *ND* respectively for each irrigated crop type *irc* starting from the total sector output *XP*. The output cost *PX* (equation (4.3)) is a linear combination of the *PVA* and *PND* prices of the two composites. The output ad-valorem tax τ^P is then added to obtain the crop market price PP (equation (4.4)).

The value added is a CES nest between the capital-labour *KL* bundle and the land-related *LND* bundle that is characterised by a σ_{VA} elasticity of substitution. Equations (4.5) and (4.6) introduce the demand functions for the two composites embedding the cost-minimisation behaviour for a CES functional form of production technology. Thus PVA calculated in equation (4.7) defines the aggregated prices of top-level factor nesting.

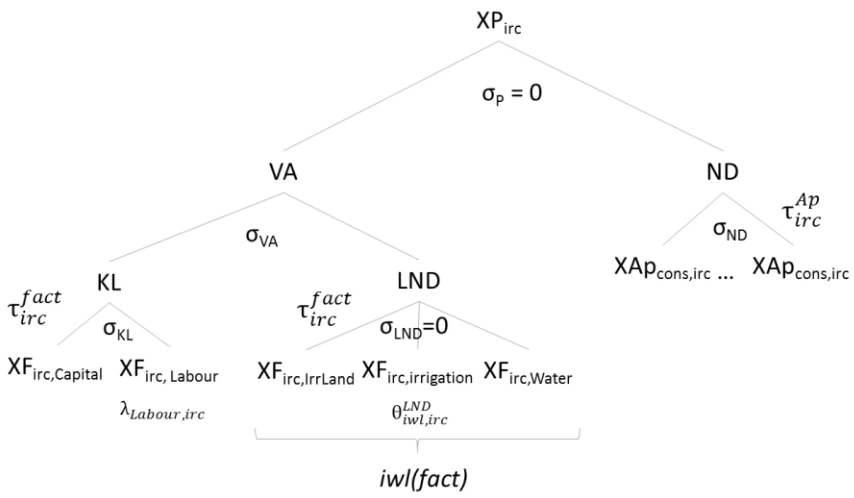

Figure 4.3 - Irrigated crops - production function

$$VA_{irc} = \alpha_{VA}^{irc}\, XP_{irc} \tag{4.1}$$

$$ND_{irc} = \alpha_{ND}^{irc}\, XP_{irc} \tag{4.2}$$

$$PX_{irc} = \alpha_{VA}^{irc}\, PVA_{irc} + \alpha_{ND}^{irc}\, PND_{irc} \tag{4.3}$$

$$PP_{irc} = \left(1 + \tau_{irc}^{P}\right) * PX_{irc} \tag{4.4}$$

$$KL_{irc} = \alpha_{KL,irc}^{VAN} \left(\frac{PVA_{irc}}{PKL_{irc}}\right)^{\sigma_{VA}^{irc}} VA_{irc} \tag{4.5}$$

$$LND_{irc} = \alpha_{LND,irc}^{VAN} \left(\frac{PVA_{irc}}{PLND_{irc}}\right)^{\sigma_{VA}^{irc}} VA_{irc} \tag{4.6}$$

$$PVA_{irc} = \left(\alpha_{KL,irc}^{VAN} * (PKL_{irc})^{1-\sigma_{VA}^{irc}} + \alpha_{LND,irc}^{VAN} * (PLND_{irc})^{1-\sigma_{VA}^{irc}}\right)^{\frac{1}{1-\sigma_{VA}^{irc}}} \tag{4.7}$$

Capital and labour are the inputs into the *KL* bundle with a non-zero σ_{KL} elasticity of substitution. The demand *XF* for each of the two components is calculated using equation (4.8). A productivity parameter λ_{kl} is added and is endogenised for labour in the model dynamic calibration stage in order to achieve the GDP growth targets for every region. The price *PKL* is calculated similarly to *PVA* and includes the productivity change effects through the λ_{kl} parameter (equation (4.9)).

$$XF_{kl}^{irc} = \alpha_{kl,irc}^{KL} * \left(\lambda_{kl,irc}\right)^{\sigma_{KL}^{irc}-1} \left(\frac{PKL_{irc}}{(1+\tau_{kl}^{F})PF_{kl}}\right)^{\sigma_{KL}^{irc}} KL_{irc} \tag{4.8}$$

$$PKL_{irc} = \left(\sum_{kl} \alpha_{kl,irc}^{KL} * \left(\frac{\left(1+\tau_{kl}^{F}\right)PF_{kl}}{\lambda_{kl,irc}}\right)^{1-\sigma_{KL}^{irc}}\right)^{\frac{1}{1-\sigma_{VA}^{irc}}} \tag{4.9}$$

The land-related bundle *LND* represents a Leontief grouping of three factors of production *iwl*: *IrrLand* (irrigated land), *Irrigation* and *Water*. The perfect complement specification implied by the zero elasticity between these factors is based on the assumption that irrigated land cannot be characterised as such without the use of the irrigation equipment and water. The demand variables *XF* for each are calculated in equation block (4.10). A productivity parameter $\theta_{iwl,irc}^{IRR}$ is added to account for yield changes in irrigated crop production taken individually for each crop class. This parameter plays an important role in the model simulations e.g. yield improvements due to technological change, water intensity changes induced by climate change. *PLND* is the price of the land-related bundle taking into account the factor use tax τ_{iwl}^{F} specific to each *iwl* factor (equation (4.11)).

$$XF_{iwl}^{irc} = \alpha_{iwl,irc}^{LND} \frac{LND_{irc}}{\theta_{iwl,irc}^{LND}} \tag{4.10}$$

$$PLND_{irc} = \sum_{iwl} \alpha^{LND}_{ilw,,irc} * \frac{(1+\tau^{F}_{iwl})PF_{iwl}}{\theta^{LND}_{irc}} \tag{4.11}$$

The intermediate demand bundle *ND* is a CES composite of the different Armington goods *cons* entering crop production. The demand for each good is defined in equation (4.12) and the price of the *ND* composite in equation (4.13). The elasticity σ_{ND} in the GTAP database is zero suggesting a rigid Leontief bundling of intermediate demand. However, in the RESCU-Water model σ_{ND} is initiated to a value of 2 to enable the flexibility of production technologies to adapt to water scarcity through the substitution of supplied water with other production inputs. This specification is applicable to all production typologies but the water-intensive industrial sectors.

$$XAp_{cons,irc} = a^{ND}_{cons,irc}\left(\frac{PND_{irc}}{(1+\tau^{Ap}_{cons,irc})PA_{cons}}\right)^{\sigma^{irc}_{ND}} ND_{irc} \tag{4.12}$$

$$PND_{irc} = \left(\sum_{cons} a^{ND}_{cons,irc} * \left((1+\tau^{Ap}_{cons,irc})PA_{cons}\right)^{1-\sigma^{irc}_{ND}}\right)^{\frac{1}{1-\sigma^{irc}_{ND}}} \tag{4.13}$$

Rainfed crop production

The production functions of rainfed crops *rfc* are to a large extent similar to those of irrigated crops (Figure 4.4). The main difference consists in the simplification of land-related inputs, with the *LND* composite from irrigated production being replaced by the direct use of rainfed land $XF_{RfLand,rfc}$. Thus, equations (4.6) and (4.7) are replaced by equations (4.14) and (4.15). Again, the inclusion of the $\theta_{RfLand,rfc}$ productivity parameter allows for the crop-specific implementation of yield changes.

$$XF_{RfLand,rfc} = \alpha^{VAN}_{RfLand,rfc} * (\theta_{RfLand,rfc})^{\sigma^{rfc}_{VA}-1}\left(\frac{PVA_{rfc}}{(1+\tau^{F}_{RfLand,rfc})PF_{RfLand}}\right)^{\sigma^{rfc}_{VA}} VA_{rfc} \tag{4.14}$$

$$PVA_{rfc} = \left(\alpha^{VAN}_{KL,rfc} * (PKL_{rfc})^{1-\sigma^{rfc}_{VA}} + \alpha^{VAN}_{RfLand,rfc} * \left(\frac{(1+\tau^{F}_{RfLand,rfc})PF_{RfLand}}{\theta_{RfLand,rfc}}\right)^{1-\sigma^{rfc}_{VA}}\right)^{\frac{1}{1-\sigma^{rfc}_{VA}}} \tag{4.15}$$

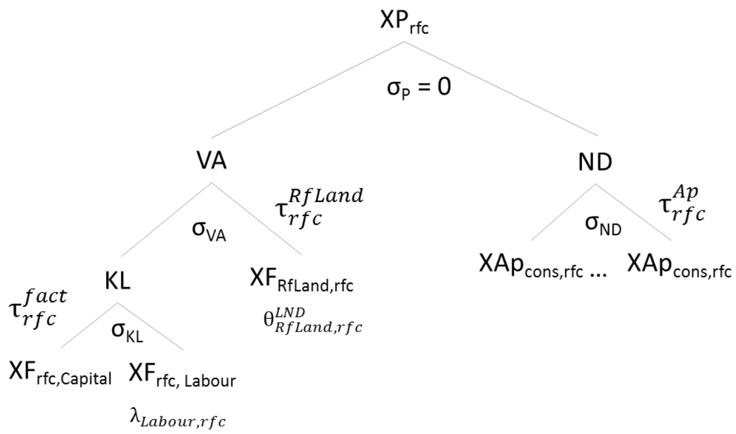

Figure 4.4 - Rainfed crops - production function

Non-crop self-abstracting sectors

Production functions for self-abstracting sectors other than crops *sai* introduce the use of water endowments in the top-level Leontief nest (Figure 4.5) and therefore assume the use of this factor to be done in fixed shares relative to sectoral output. Whilst a productivity parameter is envisaged in order to reflect the changes in the way water is used within the economy, the main specification does not allow for a substitution between water endowment uses and other factors of production or intermediate goods. The essence of this assumption is that without the use of water, these sectors (livestock, thermal power, industrial and municipal water supply) could not operate.

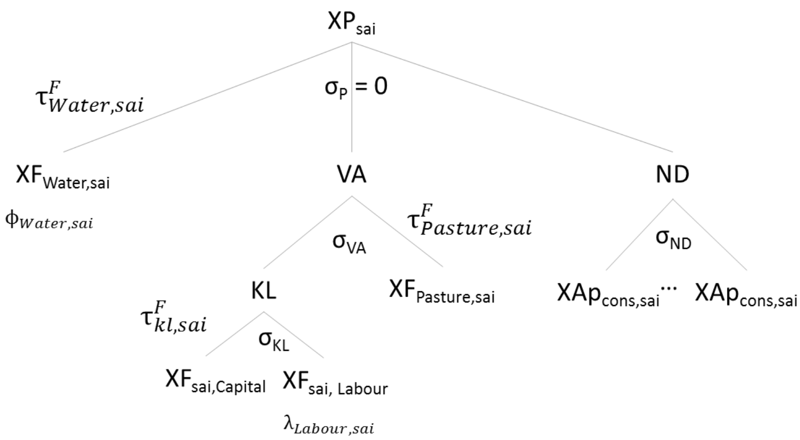

Figure 4.5 - Non-crop self-abstracting sectors - production function

In the model, equation (4.16) is added to equation blocks (4.1) and (4.2) attached to the *sai* sectors in order to introduce the demand for water endowments $XF_{Water,sai}$ at the top-level. The productivity parameter $\phi_{Water,sai}$ is added. $\phi_{Water,sai}$ is exogenously specified and changes over time in order to capture the technological or structural changes occurring in the self-abstracting sectors and the downstream supplied users, namely:

- For thermal power, changes in cooling technologies leading to lower withdrawals per unit of output
- Structural changes in industrial water uses as the economy develops and moves towards more water productive activities
- Municipal water efficiency gains of households and services as growth in income per capita allows for the adoption of more water-efficient appliances.

$$XF_{Water,sai} = \alpha_{Water}^{sai} \frac{XP_{sai}}{\phi_{Water,sai}} \tag{4.16}$$

$$PX_{sai} = \alpha_{VA}^{sai}\, PVA_{sai} + \alpha_{ND}^{sai}\, PND_{sai} + \frac{\alpha_{Water}^{sai}\left(1 + \tau_{Water,sai}^{F}\right)PF_{Water}}{\phi_{Water,sai}} \tag{4.17}$$

In water scarcity scenarios, the shadow price of water PF_{Water} is included in the production cost of self-abstracting sectors PX_{sai}. For these sectors, equation (4.17) replaces equation block (4.3) to include this additional cost divided by the sector-specific water productivity. In the current model simulations, the ad-valorem factor use tax $\tau_{Water,sai}^{F}$ is considered to be zero. However, this could be modified to introduce additional taxation or subsidies and thus influence the burden-bearing of water scarcity costs of the different users.

For livestock, the $XF_{Pasture,livestock}$ demand of *Pasture* land is introduced similarly to rainfed land in rainfed production. Therefore equation (4.14) is replaced by equation (4.18) below. The price PVA for livestock is also modified accordingly – equation (4.19). All the other *sai* sectors do not have any land-related inputs present in the GTAP database and hence this equation type is not applicable.

$$XF_{Pasture,livestock} = \alpha_{Pasture,livestock}^{VAN} \left(\frac{PVA_{livestock}}{(1+\tau_{Pasture,livestock}^{F})PF_{Pasture}}\right)^{\sigma_{VA}^{livestock}} VA_{livestock} \tag{4.18}$$

$$PVA_{livestock} = \left(\alpha_{KL,livestock}^{VAN} * (PKL_{livestock})^{1-\sigma_{VA}^{livestock}} + \alpha_{Pasture,livestock}^{VAN}\left(\left(1+\tau_{Pasture,livestock}^{F}\right)PF_{Pasture}\right)^{1-\sigma_{VA}^{livestock}}\right)^{\frac{1}{1-\sigma_{VA}^{livestock}}} \tag{4.19}$$

Water-intensive industrial sectors

The production function of water-intensive sectors *ind* isolates the demand of industrial water *iwt* from all other intermediate goods through a two-level nesting of the *ND* composite (Figure

4.6). This separation limits the flexibility of these sectors to substitute away from water inputs. At the first level, the intermediate Armington demand $XAp_{iwt,irc}$ is separated from that of all other goods *ND2* through a CES nest – equations (4.20) and (4.21). Equation (4.22) defines the price of the top-level intermediate composite. At the second level, the *ND2* composite groups all the other demand commodities *nwc* through a CES specification for the intermediate demand functions and the *ND2* price (equation blocks (4.23) and (4.24) respectively). The σ_{ND2} elasticity of substitution has a value of 2, similarly to the intermediate good nesting in the other sectors. The value for σ_{ND1} is set to 0.01 to indicate a low substitutability of industrial water by other input types.

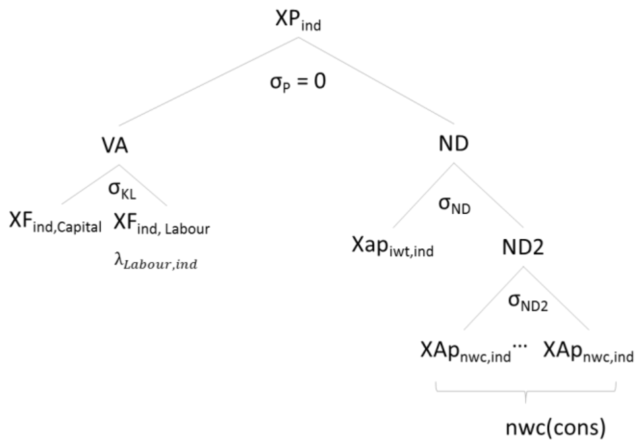

Figure 4.6 - Equivalent production function for water-intensive industrial sectors (ind)

In the added-value nesting, the industrial sectors do not have any land inputs in the GTAP database. The VA nest is thus composed only from capital and labour inputs as the land input equations (i.e. equation (4.14) for rainfed crops) are not applicable here.

$$XAp_{"iwt",ind} = a^{ND}_{"iwt",ind}\left(\frac{PND_{ind}}{(1+\tau^{Ap}_{"iwt",ind})PA_{ind}}\right)^{\sigma^{ind}_{ND}} ND_{ind} \tag{4.20}$$

$$ND2_{cons} = a^{ND}_{ND2,cons}\left(\frac{PND_{cons}}{PND2_{cons}}\right)^{\sigma^{ind}_{ND}} ND_{ind} \tag{4.21}$$

$$PND_{ind} = \left(a^{ND}_{"iwt",ind} * \left((1+\tau^{Ap}_{ind})PA_{"iwt"}\right)^{1-\sigma^{ind}_{ND}} + \alpha^{ind}_{ND2,cons} * (PND2_{ind})^{1-\sigma^{ind}_{ND}}\right)^{\frac{1}{1-\sigma^{ind}_{ND}}} \tag{4.22}$$

$$XAp_{nwc,ind} = a^{ND2}_{nwc,ind}\left(\frac{PND2_{ind}}{(1+\tau^{Ap}_{nwc,ind})PA_{nwc}}\right)^{\sigma^{ind}_{ND2}} ND2_{ind} \tag{4.23}$$

$$PND2_{ind} = \left(\sum_{nwc} a^{ND2}_{nwc,ind} * \left((1+\tau^{Ap}_{nwc,ind})PA_{nwc}\right)^{1-\sigma^{ind}_{ND2}}\right)^{\frac{1}{1-\sigma^{ind}_{ND2}}} \tag{4.24}$$

Non- water-intensive sectors

The remaining sectors, the water-flexible industrial sectors (transport and non-thermal power) and the services sectors, have a simplified production function. The first group, as opposed to water-intensive activities, bundle industrial water inputs with all other intermediate demand goods and allow thus some flexibility in substituting water with other input types. Services only differ from industrial sectors by removing the specification of industrial water inputs as these are zero for services in the RESCU-Water database (see Chapter 5 for GTAP database splitting of the water sector). The equivalent production function comprises only one level for intermediate demand nesting (Figure 4.7). These sectors employ municipal water *mwt* inputs which are bundled with all other intermediate demand commodities. Supplied water for both user types is thus treated like any other commodity.

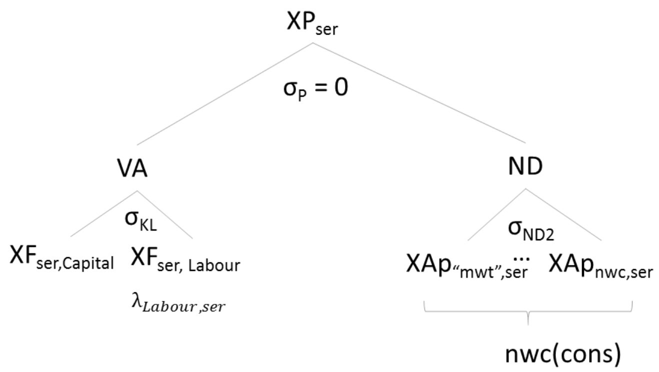

Figure 4.7 - Equivalent production function for services sectors (ser)

4.4.2.2. Demand commodities

The RESCU model makes a distinction between traded commodities and demand commodities and is applicable to crops and power generation where more than one traded variety is produced for one demand commodity (e.g. electricity coming from both thermal and non-thermal power generation). The different production varieties are combined in a CES bundle (equation (4.25)) to then become a demand commodity *cons* with a specific market price (equation (4.26)). The elasticity of substitution σ_{cons} between production commodities is specified distinctly for each demand commodity depending on the inertia of switching the production from one variety to another. For electricity, σ_{cons} has a value of 5 as found in the ENV-LINKAGES model (Chateau et al. 2014), whilst for crops, this has a value of 10 to mark an almost perfect substitutability.

$$XP_k^{cons} = \beta_k^{cons} \left(\frac{PC_{cons}}{PP_k}\right)^{\sigma_{cons}} XC_{cons} \tag{4.25}$$

$$PC_{cons} = \left(\sum_k \beta_k^{cons} * (PP_k)^{1-\sigma_{cons}}\right)^{\frac{1}{1-\sigma_{cons}}} \tag{4.26}$$

4.4.2.3. International trade

The imported and domestic varieties are considered imperfect substitutes in line with the Armington assumption. Thus commodities entering the intermediate and final demand are combined into Armington goods which are introduced as CES bundles of the two varieties – equation (4.31). Equations (4.27) and (4.28) define the demand functions of the domestic and imported variety respectively.

$$XMT_{cons} = \beta_{cons}^M \left(\frac{PA_{cons}}{PMT_{cons}}\right)^{\sigma_M} XA_{cons} \tag{4.27}$$

$$XD_{cons} = \beta_{cons}^D \left(\frac{PA_{cons}}{PD_{cons}}\right)^{\sigma_M} XA_{cons} \tag{4.28}$$

$$PA_{cons} = \left(\beta_{cons}^M * \left(PMT_{cons,s}\right)^{1-\sigma_M} + \beta_{cons}^D * \left(PD_{cons,s}\right)^{1-\sigma_M}\right)^{\frac{1}{1-\sigma_M}} \tag{4.29}$$

The model also differentiates imports by their source region *s* in the second step through a CES nesting of imports of demand commodities specified by trading pair $XM_{cons,s}$. Equation block (4.30) introduces the demand for imports from each source region *s* which takes into account the tariff-inclusive import price *PM*. The composite import price for each commodity *cons* is defined in equation (4.31).

$$XM_{cons,s} = \beta_{cons,s}^W \left(\frac{PMT_{cons}}{PM_{cons,s}}\right)^{\sigma_W} XMT_{cons} \tag{4.30}$$

$$PMT_{cons} = \left(\sum_s \beta_{cons,s}^W * \left(PM_{cons,s}\right)^{1-\sigma_w}\right)^{\frac{1}{1-\sigma_W}} \tag{4.31}$$

For exports, the total supply of each demand commodity XC_{cons} minus contributions to international trade XMg_{cons} (applicable to transport commodities) is allocated to the domestic (4.32) and to export markets (4.33) through a CET function. The specification reflects the non-frictionless adjustment of the production process when switching from one destination market to the other that induces a price differential between the domestic and export varieties (equation (4.34)).

$$XD_{cons} = \gamma_{cons}^D \left(\frac{PD_{cons}}{PC_{cons}}\right)^{\sigma_X} (XC_{cons} - XMg_{cons}) \tag{4.32}$$

$$ES_{cons} = \gamma^{E}_{cons} \left(\frac{PE_{cons}}{PC_{cons}}\right)^{\sigma_X} (XC_{cons} - XMg_{cons}) \quad (4.33)$$

$$PC_{cons} = (\gamma^{D}_{cons} * (PD_{cons})^{1+\sigma_X} + \gamma^{E}_{cons} * (PE_{cons})^{1+\sigma_X})^{\frac{1}{1+\sigma_X}} \quad (4.34)$$

Two quantity conservation conditions are introduced in equations (4.35) and (4.36). In the first, total exported quantities of every source region *s* are equalled to total bilateral trade flows *WTF* originating from this region. In the second, all imports specified bilaterally in equation (4.30) are equalled to *WTF.*

Next, a series of price conversions are introduced to account for trade tariffs and transport margins. Equation (4.37) adds the export taxes $\tau^{E}_{cons,s,d}$ specific to every trade link *(s,d)* to compute the CIF world trade prices *WPE*. The FOB prices *WPM* are calculated by adding transport costs which are accounted as ad-valorem margins $\zeta_{cons,s,d}$ (equation (4.38)). Trade tariffs $\tau^{M}_{cons,s,d}$ are added in equation (4.39) to determine the price of imports *PM* for importing regions *d*.

$$ES_{cons,s} = \sum_{d} WTF_{s,d,cons,} \quad (4.35)$$

$$WTF_{s,d,cons} = XM_{s,d,cons} \quad (4.36)$$

$$WPE_{cons,s,d} = (1 + \tau^{E}_{cons,s,d})PE_{cons,s} \quad (4.37)$$

$$WPM_{cons,s,d} = (1 + \zeta_{cons,s,d})WPE_{cons,s,d} \quad (4.38)$$

$$PM_{cons,s,d} = (1 + \tau^{M}_{cons,s,d})WPM_{cons,s,d} \quad (4.39)$$

International transport is considered a global sector to which model regions contribute in fixed shares. The total value of international transport is defined in equation (4.40) by summing up all the transport margins applied as ad-valorem costs and which are specific to every commodity and every source *s* – destination *d* trading pair. The regional demand for international transport $AXMg_r$ is introduced in equation (4.41) as a share of global demand *WXMg*. The global price of the international transport is calculated in equation (4.42) as a weighted average of regional transport prices $APMg_r$. In a second stage, the regional supply is composed of a subset *tr* of demand commodities *cons* through a Leontief nesting (equation (4.43)). Equation (4.44) determines the regional price of international transport, again as a weighted average of the price of transport commodities PC_{tr}.

$$WPMg * WXMg = \sum_{s} \sum_{d} \zeta_{cons,s,d} WPE_{s,d,cons} WTF_{s,d,cons} \quad (4.40)$$

$$AXMg_r = \alpha^{T}_{r} WXMg \quad (4.41)$$

$$WPMg = \sum_{r} \alpha^{T}_{r} APMg_r \tag{4.42}$$

$$XMg_{r,tr} = \alpha^{Mg}_{r,tr} AXMg_r \tag{4.43}$$

$$APMg_r = \sum_{tr} \alpha^{Mg}_{r,tr} PC_{tr} \tag{4.44}$$

4.4.2.4. Final demand

Final demand is driven by three agent types – households, government and investment, with each having a separate behaviour implemented through demand functions.

Households

Household demand is determined through a Linear Expenditure System (Stone-Geary) which defines utility as:

$$U(cons) = \prod_{cons} (XAc_{cons} - \mu_{cons})^{\alpha^{LES}_{cons}}$$

where the μ_{cons} parameters represent the subsistence components of the consumption of demand commodity *cons.* The inclusion of subsistence consumption enables the differentiation between consumption goods in terms of income elasticities. This distinction is an important specification in the water scarcity impacts analysis in relation to food demand. In the model specification, utility is maximised subject to the budget constraints Y_c through the demand equation (4.45). The index *ccons* is an alias for the demand commodity index *cons* and is used here for the subtraction of total expenditure on subsistence consumption from disposable income destined to consumption Y_c.

$$XAc_{cons} = \mu_{cons} + \frac{\alpha^{LES}_{cons}}{(1+\tau^{Ac}_{cons})PA_{cons}} \left(Y_c - \sum_{ccons} \mu_{ccons}(1+\tau^{Ac}_{ccons})\, PA_{ccons} \right) \tag{4.45}$$

Government and investment

Both government and the investment sector maintain their commodity demand in fixed shares relative to their composite *FD* through the use of a Leontief specification – equation block (4.46). The demand for FD is restricted by the budget constraint of each of the two *f* agents and is depended on each agent's composite price *PFD* – equation (4.47).

$$XAf_{cons,f} = \alpha_{cons,f} FD_f \tag{4.46}$$

$$PFD_{cons} = \alpha_{cons,f} \left(1+\tau^{Af}_{cons,f}\right) PA_{cons} \tag{4.47}$$

4.4.2.5. Income balance

Households

Household income is composed of all wage and factor rents. The revenue from each factor is equal to the regional factor supply *FS* multiplied by the factor value at market prices *PF* – equation (4.48). A number of deductions are made before allocating the disposable income to consumption. First, capital depreciation *DeprY* is subtracted from income *YH* net of income taxation (equation (4.49)). Depreciation is calculated as a constant share δ_K of capital stock at the start of the simulation year *KStock* valuated at the investment good composite price PFD_{inv} (equation (4.50)).

Next, the obtained disposable income *Yd* is allocated to savings and consumption (equation (4.51)). Household savings are calculated through a marginal savings propensity *mps* which reflects the base year savings pattern (equation (4.52)). These are then adjusted using the *adjSavings* variable. For the model dynamic baseline, *adjSavings* is endogenised to enable the achievement of a pre-set investment schedule in every region.

$$YH = \sum_{fact} PF_{fact} FS_{fact} \tag{4.48}$$

$$Yd = (1-\kappa)YH - DeprY \tag{4.49}$$

$$DeprY = \delta_K \ KStock \ PFD_{inv} \tag{4.50}$$

$$Yc = Yd - SH \tag{4.51}$$

$$SH = adjSavings * \ mps * Yd \tag{4.52}$$

Government

Government revenues (equation (4.53)) are composed of all taxes collected – sales taxation (τ_{cons}^{Ap}, $\tau_{cons,f}^{Ap}$, τ_{cons}^{Ac}) , factor use taxation ($\tau_{fact,k}^{F}$) , output taxation (τ_i^P), income taxation (κ), import tariffs *TarY* calculated in equation and export taxation (τ_{cons}^{E}). Import tariffs *TarY* are calculated using tariffs $\tau_{s,r,cons}^{M}$ applied to the FOB bilateral price *WPM* between destination *r* and source region *s* (equation (4.54)).

$$\begin{aligned} YG = {} & \textstyle\sum_{cons} PA_{cons}\left(\sum_i \tau_{cons}^{Ap} XAp_{cons,k} + \sum_f \tau_{cons,f}^{Ap} XAf_{cons,f} + \tau_{cons}^{Ac} XAc_{cons}\right) + \\ & + \textstyle\sum_{fact}\sum_k \tau_{fact,k}^{F} PF_{fact} XF_{fact,k} \ + \ \sum_i \tau_i^P PX_i XP_i + \ \kappa YH + TarY + \\ & \textstyle\sum_{cons} \ \tau_{cons}^{E} PE_{cons} * WTF_{cons} \end{aligned} \tag{4.53}$$

$$TarY_r = \sum_{cons}\sum_{s} \tau_{s,r,cons}^{M} WPM_{s,r,cons} WTF_{s,r,cons} \tag{4.54}$$

Government spending is equalled to revenue *YG* after deducting government savings S_{gov} (equation (4.55)). Savings are specified in equation (4.56) as a fixed share χ_{gov} of nominal GDP that is calibrated onto the base year GTAP data.

$$PFD_{gov}FD_{gov} = YG - S_{gov} \tag{4.55}$$

$$S_{gov} = \chi_{gov}GDPMP \tag{4.56}$$

Investment

Total investment represents the sum of all savings (household, government and foreign) plus capital depreciation (equation (4.57)). A regional investment share relative to nominal GDP is calculated (equation (4.58)) and is fixed in the baseline according to an exogenous investment schedule which is achieved through adjustments of household savings SH as specified in equation (4.52).

$$PFD_{inv,r}FD_{inv,r} = SH_r + S_{gov,r} + S_{inv,r} + DeprY_r \tag{4.57}$$

$$InvSh_r = \frac{PFD_{inv,r}FD_{inv,r}}{GDPMP_r} \tag{4.58}$$

$$S_{inv,rn} = P * \bar{S}_{inv,rn} \tag{4.59}$$

$$\sum_r S_{inv,r} = 0 \tag{4.60}$$

Equation (4.59) determines the levels of foreign savings $S_{inv,rn}$ for all regions minus the numéraire. The new levels are a product between the numéraire price P and the base year regional foreign investment $\bar{S}_{inv,rn}$. The drop of the equation for the numéraire region is done to meet the global Walras' Law. Equation (4.60) enforces a global consistency of flows of foreign savings – all outflows must equal all inflows.

4.4.2.6. Factor markets

Factor supply *FS* is exogenously specified for capital, labour and pasture land, and is endogenised for arable land (rainfed *RfLand* and irrigated *IrrLand*) and irrigation. In model scenarios where water scarcity is considered, and thus water as an endowment is integrated into the model equations, the water factor supply is exogenous and is subject to restrictions in water withdrawals in water-scarce regions.

In simulations where water scarcity is not considered, the supply of water FS_{Water} and the sectoral demand for water endowments $XF_{Water,i}$ are calibrated to be zero and thus these variables together with the market price of water as endowment PF_{Water} are functionally excluded from the model solution.

Land used in crop production is supplied in two stages. First, an overall supply of arable land *Aland* is decided through a logistic function (equation (4.61)). The supply takes into account constraints in land conversion possibilities given by an upper limit $LandMax_r$ which is region-specific and is informed by GAEZ land suitability data (Fischer et al. 2011). Arable land availability is thus a function of market prices, with an adjustment following relative changes of land prices *PAland* to a regional market price index *PABS*.

Next, arable land is allocated across rainfed and irrigated land using a CET function by using the demand and supply equations (4.62) and (4.63) for the two land types. The σ_{AL} elasticity of transformation determines the land conversion possibilities from rainfed to irrigated land and conversely.

$$Aland_r = \frac{LandMax_r}{1 + \varepsilon_r^{LND} e^{k_{LND}\frac{PALand_r}{PABS_r}}} \quad (4.61)$$

$$FS_{RfLand,r} = \gamma_{RfLand,r}^{AL} \left(\frac{PF_{RfLand,r}}{PAland_r}\right)^{\sigma_{AL}} Aland_r \quad (4.62)$$

$$FS_{IrrLand,r} = \gamma_{IrrLand,r}^{AL} \left(\frac{PF_{IrrLand,r}}{PAland_r}\right)^{\sigma_{AL}} Aland_r \quad (4.63)$$

The irrigation supply is also introduced as a logistic function, similarly to arable land (equation (4.64)). This specification enables the availability of irrigation as a facility for crop production to expand or contract as a function of price changes of the irrigation prices $PF_{Irrigation}$ relative to the market price index. It is assumed that the initial price elasticities of the supply functions for arable land and irrigation are similar so that irrigation supply would not be a significant additional constraint in crop production. Hence the slope parameters k_{LND} and k_{IRR} of the two supply functions are identical but differentiated between developed and developing regions.

$$FS_{irrigation,r} = \frac{IrrMax_r}{1 + \varepsilon_r^{IRR} e^{k_{IRR}\frac{PF_{irrigation,r_r}}{PABS_r}}} FS_{irrigation,r,0} \quad (4.64)$$

Market clearing for all factors is established through the condition that the sum of factor demand by all productive sectors equals supply (equation (4.65)). This condition is met by implicitly adjusting the market price of factors *PF*.

$$FS_{factor} = \sum_{i} XF_{factor,i} \tag{4.65}$$

4.4.2.7. Commodity markets

Market equilibrium is assumed for all traded commodities in all markets (domestic and international). Equation (4.66) defines the market clearing for the domestic market. The right side of the equation represents total demand of traded commodity *cons* by all intermediate sector *i* and by all final demand agents. This is equalled to the total domestic supply *XA* on the left side which is the Armington nest of domestic supply *XD* and imports *PMT* as defined in equations (4.27) and (4.28).

$$XA_{cons} = \sum_{i} XAp_{cons,i} + \sum_{f} XAf_{cons,f} + XAc_{cons} \tag{4.66}$$

The market equilibrium for domestic commodities is obtained through equality of XD values for supply (equation (4.32)) and demand (equation (4.27)) by implicitly adjusting the price of domestic varieties *PD*. Similarly, the supply of exports (equation (4.33))and foreign demand by source region (equation (4.35)) is obtained through adjustments of export prices *PE*.

4.4.2.8. Global Walras' Law

Due to the Walras' Law at a regional level, one variable in every region becomes dependent, and thus one equation needs to be dropped in order to ensure that the model is square i.e. number of independent variables equals the number of equations. The equations that are taken out refer to the regional current account deficits (equation (4.67)) which are implicitly kept at the base year levels. In the deficit calculation, in line with the calibrated values from the GTAP data, it is assumed that no world transfers are occurring between institutions of different regions e.g. foreign aid.

$$CA_{r,0} = \sum_{cons} \sum_{rr} WPE_{r,rr,cons} WTF_{cons,r,rr} - WPM_{rr,r,cons} WTF_{cons,rr,r}) + APMg_r AXMg_r + P * S_{inv,r} \tag{4.67}$$

The conditions derived from the two applications of Walras' Law – at a regional level, from the equation above, and at a global level, from the constant foreign investment of the numéraire region implied by equations (4.59) and (4.60) – are tested for every model solution. Meeting these conditions guarantee the global consistency of the model results.

4.4.2.9. Numéraire

Similarly to the LINKAGE model, RESCU adopts a numéraire which is calculated as a composite price of manufacturing exports by the group of developed regions *dr*. This is determined relative to base year world price values *WPE* and trade flows *WTF* – equation (4.68). The numéraire is fixed to 1 in all simulations and serves as a reference for all other changes in prices.

$$P = \frac{\sum_{manu}\sum_{rr}\sum_{dr} WPE_{dr,rr,manu} * WTF_{dr,rr,manu,0}}{\sum_{manu}\sum_{rr}\sum_{dr} WPE_{dr,rr,manu,0} * WTF_{dr,rr,manu,0}} \tag{4.68}$$

4.4.2.10. Other indicators and prices

A regional price change PINDEX calculated in equation (4.69) as a relative price change of traded commodities $PC_{cons,r}$ with respect to base year prices $PC_{cons,r,0}$. *PABS* is the price index of aggregate domestic absorption and is calculated in equation (4.70) as a function of changes in prices of the Armington goods. *PABS* is used in the land and irrigation supply equations (4.61) and (4.64) as a reference price for the contraction or expansion in factor availability.

As macro-economic indicators, the model calculates *GDPMP* (equation (4.71)) as the regional nominal GDP at market prices by summing up the gross value of total demand of Armington composites, the value of net trade and that of the regional contribution to international transport. *GDPMP* is also used in the government savings equation. The real GDP is calculated similarly by using the base year price sets – equation (4.72).

$$PINDEX_r = \frac{\sum_{cons} PC_{cons,r} * XC_{cons,r}}{\sum_{cons} PC_{cons,r,0} * XC_{cons,r}} \tag{4.69}$$

$$PABS_r = \frac{\sum_{cons} PA_{cons,r} * XA_{cons,r}}{\sum_{cons} PA_{cons,r,0} * XA_{cons,r}} \tag{4.70}$$

$$\begin{aligned} GDPMP_r = \sum_{cons} PA_{cons,r} \Bigg(& \sum_{i} (1+\tau^{Ap}_{cons,r}) XAp_{cons,k,r} + \sum_{f} (1+\tau^{Ap}_{cons,f,r}) XAf_{cons,f,r} \\ & + (1+\tau^{Ac}_{cons,r}) XAc_{cons,r} \Bigg) \\ & + \sum_{cons}\sum_{rr} WPE_{r,rr,cons} WTF_{cons,r,rr} - WPM_{rr,r,cons} * WTF_{cons,rr,r}) \\ & + APMg_r AXMg_r \end{aligned} \tag{4.71}$$

$$\begin{aligned} RGDPMP_r = \sum_{cons} PA_{cons,r,0} \Bigg(& \sum_{i} (1+\tau^{Ap}_{cons,r}) XAp_{cons,k,r} + \sum_{f} (1+\tau^{Ap}_{cons,f,r}) XAf_{cons,f,r} \\ & + (1+\tau^{Ac}_{cons,r}) XAc_{cons,r} \Bigg) \\ & + \sum_{cons}\sum_{rr} (WPE_{r,rr,cons,0} WTF_{cons,r,rr} - WPM_{rr,r,cons,0} * WTF_{cons,rr,r}) \\ & + APMg_{r,0} AXMg_r \end{aligned} \tag{4.72}$$

4.4.3. Model dynamics

The model dynamics refer to the changes which occur in between two consecutive model solutions. These changes alter production technologies given changes in factor availability and factor sectoral productivity but also influence household demand by including alterations to consumption patterns induced by demographic evolution.

Capital is determined by investment and implicitly by real GDP considering the investment-driven model closure and the inclusion of investment targets as a share of real GDP (equation (4.58)). Growth in real GDP is specified exogenously through rates $g_{r,t}^{RGDP}$ derived through output data from other modelling frameworks. These changes are applied to *t-1* GDP values to determine the current *t* real GDP targets (equation (4.73)). In this thesis, the model dynamic calibration is done using the GDP growth rates published through the SSP database[8].

The end-of-simulation capital stock is then calculated to factor in depreciation and investment (equation (4.74)). The updated capital stock determines a growth in capital availability which is used as a multiplier for capital supply in the next simulation period *t+1.*

$$RGDPMP_{r,t} = RGDPMP_{r,t-1} * g_{r,t}^{RGDP} \tag{4.73}$$

$$Kstock_{r,t} = Kstock_{r,t-1} - Depr_{r,t} + FD_{inv,r,t} \tag{4.74}$$

$$FS_{Capital,r,t+1} = FS_{Capital,r,t} * \frac{Kstock_t}{Kstock_{t-1}} \tag{4.75}$$

Labour is considered to be fully employed and its supply follows the changes in active population at the regional level. $g_{r,t}^{L}$ annual labour growth rates are exogenous and are calibrated according to the different active population growth assumptions (equation (4.76)).

$$FS_{Labour,r,t+1} = FS_{Labour,r,t} * g_{r,t+1}^{L} \tag{4.76}$$

In addition to changes in factor supply, the labour productivity variable $\lambda_{Labour,i}$ as laid out in equation (4.8) is endonenised to enable the model solution to reach the real GDP targets of equation (4.73). The productivity gains are region-wide but differentiate between agricultural and non-agricultural sectors, by assuming the labour productivity increases in agriculture to be half those in the other economic sectors. This distinction is similar to other global CGE models. For instance, the LINKAGE model includes the same labour-augmenting mechanism using the $\lambda_{Labour,i}$ variable but endogenises this only for non-agricultural sectors.

[8] https://tntcat.iiasa.ac.at/SspDb/

On the demand side, the household consumption patterns are modified by updating subsistence levels $\mu_{cons,r,t}$ to follow population growth $g_{r,t}^{POP}$ in each region – equation (4.77). These alterations enable the model to track the importance of subsistence in consumption and the way this impacts the calculation of the regional utility levels and household consumption behaviour.

$$\mu_{cons,r,t+1} = \mu_{cons,r,t} * g_{r,t+1}^{POP} \tag{4.77}$$

4.4.4. Model calibration

4.4.4.1. Production functions

The calibration of production functions implies the calculation of share parameters starting from the base year GTAP data and the elasticities of substitution adopted. For a CES nesting in a production function with a demand function of inputs that has a generic specification as in equation (4.78) below, the share parameters α_k are obtained straightforwardly by inverting the function into (4.79). In these equations X_k and P_k are the quantity and price of the k-th input, V and P are the quantity and price of the nest output. The value of these parameters are thus dependent on the base year data X_k and V and the corresponding prices. P and P_k are considered to be 1 onto which any relevant tax can be added.

$$X_k = \alpha_k \lambda_k^{\sigma-1} \left(\frac{P}{P_k}\right)^{\sigma} V \tag{4.78}$$

$$\alpha_k = \frac{1}{\lambda_k^{\sigma-1}} \left(\frac{P_k}{P}\right)^{\sigma} \frac{X_k}{V} \tag{4.79}$$

At the same time, the calibration of share parameter is dependent on the elasticity of substitution σ. For σ=0, this translates the nest into a Leontief bundle. Assuming unitary prices with no taxation and no productivity gains, (4.78) and (4.79) become (4.80) and (4.81) respectively.

$$X_k = \alpha_k V \tag{4.80}$$

$$\alpha_k = \frac{X_k}{V} \tag{4.81}$$

Table 4.3 - Elasticity values in production functions

Elasticity	Value	Source
σ_P top-level	0	GTAP
σ_{VA} top-level VA nest	ESUBVA [0.23-1.68]*	GTAP
σ_{KL} capital-labour nest	ESUBVA [0.23-1.68]*	GTAP
σ_D Armington nest	ESUBD [1.90-5.05]*	GTAP
σ_M inter-regional import substitution	ESUBM [2.60-10.1]*	GTAP
σ_{ND1} for industrial water inputs	0.01	assumption
σ_{ND2} for other inputs	2	assumption

** Dataset values from the GTAP database*

4.4.4.2. Logistic factor supply

The calibration of the logistic supply functions applicable to arable land and irrigation implies the calculation of the ε shifting parameter. Equation (4.82) calibrates ε for arable land - this parameter ensures that in the model arable land supply aligns at the equilibrium prices of 1 with the arable land endowment availability from the benchmark data.

$$\varepsilon_r^{LND} = \frac{LNDMAX_r - 1}{e^{-k_{LND}\frac{PALND_{r,o}}{PABS_{r,o}}}} = \frac{LNDMAX - 1}{e^{-k_{LND}}} \qquad (4.82)$$

The *LNDMAX* parameter is the ratio of maximum suitable arable land to benchmark arable land use and is calculated from the GAEZ land suitability database (Fischer et al. 2011) for a range of land conversion scenarios (Table 4.4). The model central scenario is that of prime land only without deforestation. The k_{LND} defines the slope of the supply curve. The assumed values for land are 0.02 for developing regions and 0.005 for developed regions. This difference is justified by tighter regulations in developed regions for land-use conversion. For the 0.02 value, the initial price elasticities of supply is in the range of 0.33-1.87%, depending on the size of *LNDMAX*, which are in line with values found in other literature (Hertel 2011; Barr et al. 2011).

Table 4.4 – Factor limits of arable land expansion from base values

Region	Prime only		Prime and good	
	with deforestation	w/o deforestation	with deforestation	w/o deforestation
Australia &NZ	5.007	3.741	12.622	9.361
China	3.594	2.351	4.893	2.851
Northeast Asia	3.049	1.304	5.758	1.407
Central Asia	6.14	5.835	9.949	9.534
Southeast Asia	1.92	1.202	3.711	1.2
South Asia	1.483	1.38	3.593	3.265
India	1.804	1.444	1.98	1.344
Canada	4.288	1.684	8.384	1.403
USA	3.457	2.104	4.617	2.088
North Latin Am	5.151	1.936	8.056	2.309
South Latin Am	6.547	4.94	9.387	6.827
Brazil	2.699	1.443	8.486	1.933
Southern Europe	1.734	1.335	2.51	1.473
Northern Europe	1.563	1.302	3.414	1.531
Eurasia	3.323	1.703	4.713	1.593
Middle East	2.436	2.245	7.376	6.866
Northern Africa	4.045	3.632	15.693	15.055
Central Africa	3.168	1.808	5.845	2.073
Sahel	5.065	4.641	13.38	10.853
Southern Africa	4.109	3.03	8.646	5.687

4.4.4.3. CET supply of arable land types

CET supply functions are used in the model for the allocation of total arable land across the two arable land types. Similarly to CES functions, the calibration of share parameters in CET functions imply the inversion of the supply equation (4.83) and (4.84). σ_{AL} represents the elasticity of transformation and is equalled to 2 in the model to reflect a moderate long-run substitutability of the two land types.

$$FS_{ltype} = \gamma_{ltype} \left(\frac{P_{ltype}}{PAland}\right)^{\sigma_{AL}} Aland \tag{4.83}$$

$$\gamma_{ltype} = \left(\frac{PAland}{P_{ltype}}\right)^{\sigma_{AL}} \frac{X_k}{V} \tag{4.84}$$

4.4.4.4. LES household demand

The calibration of the LES demand system requires the calculation of the base year subsistence consumption. The expenditure shares α_{cons}^{LES} are calculated first starting from the household income elasticity values η_{cons} obtained from the GTAP database (equation (4.85)). These are then scaled (equation (4.86)) such that their summation equals to 1 as required by the household budget constraint. The α_{cons}^{LES} values are then added to a system of equations which are solved numerically in order to obtain the subsistence values for the base year (equation (4.87)). The *LEScons* index comprises all demand commodities minus one. The construction was excluded in order to obtain a square system of *n-1* independent equations 4.87 and *n-1* variables ($\mu_{LEScons}$). The implicit assumption is that the long run income elasticity of construction is 1 and that the corresponding subsistence level for this sector is null[9].

$$\alpha_{cons}^{LES} = \frac{\eta_{cons}(1+\tau_{cons}^{Ac})PA_{cons,0}XAc_{cons,0}}{Yc_0} \tag{4.85}$$

$$\alpha_{cons}^{LES} = \frac{\alpha_{cons}^{LES}}{\sum_{ccons}\alpha_{ccons}^{LES}} \tag{4.86}$$

$$XAc_{LEScons,0} = \mu_{LEScons} + \frac{\alpha_{LEScons}^{LES}}{(1+\tau_{LEScons}^{Ac})PA_{LEScons,0}}\left(Y_c - \sum_{cons}\mu_{cons}(1+\tau_{cons}^{Ac})\,PA_{cons,0}\right) \tag{4.87}$$

4.5. Data aggregation

The model uses the economic data from the GTAP-Power database (Peters 2016). The database comprises 140 world regions and 68 economic sectors. Most regions represent individual countries, however, some of the smaller economies are grouped together into regional aggregates. GTAP-Power is an extension of GTAP version 9 (Aguiar et al. 2016) by separating electricity generation into multiple production technologies. This distinction allows for an isolation of water inputs for cooling purposes in thermal power production (coal, gas, oil and nuclear) from the other technologies (hydroelectricity, solar PV and wind power).

For the regional aggregation, it was acknowledged that crop production plays an essential role in the global use of freshwater resources. Therefore the country grouping was made based on similarities in crop growing conditions through global agro-ecological zoning (Figure 4.8). A

[9] This calibration method also implies that subsistence levels are negative for superior goods.

further distinction between regions was made based on the per capita water availability in the base year.

The sectoral structure in the RESCU-Water model details the crop sectors by distinctly representing the eight GTAP crop classes through rainfed and irrigated production. The water supply sector is also split into industrial and municipal supply to reflect the differences in water intensities of output coming out of these sectors. The initial GTAP database is thus expanded to allow for flexibility in the later aggregation and then aggregated to the RESCU-Water regional and sectoral scheme (Table 4.5).

a)

b)

c)

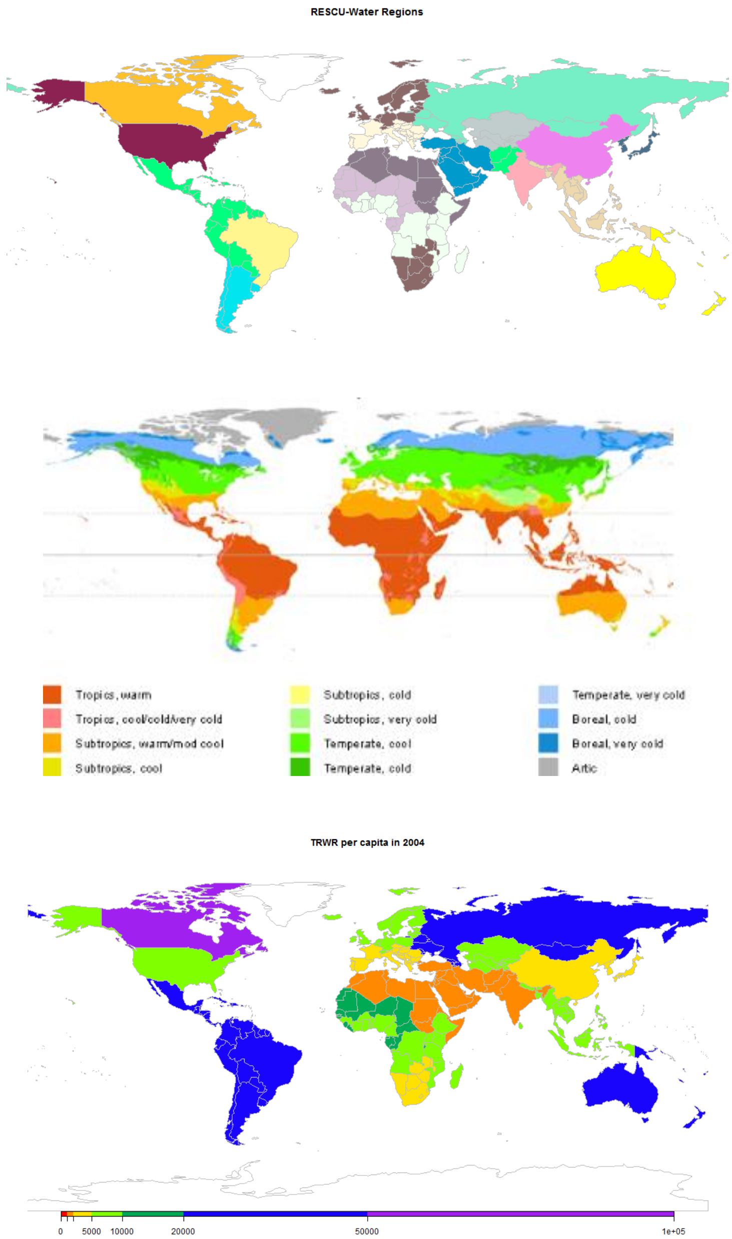

Figure 4.8 - RESCU-Water regional aggregation

a) RESCU-Water regions b) FAO global agro-ecological zoning c) renewable resources per capita by region

Table 4.5 - RESCU-Water sectoral aggregation

RESCU sector	GTAP9Power sector
PDR_IRC – paddy rice irrigated	PDR paddy rice (disaggregated)
PDR_RFC – paddy rice rainfed	
WHT_IRC – wheat rice irrigated	WHT wheat (disaggregated)
WHT_RFC – wheat rice rainfed	
GRO_IRC – other grains irrigated	GRO other grains (disaggregated)
GRO_RFC – other grains rainfed	
V_F_IRC – veg&fruits irrigated	V_F vegetables & fruits (disaggregated)
V_F _RFC – veg&fruits rainfed	
OSD_IRC – oil seeds irrigated	OSD oil seeds (disaggregated)
OSD_RFC – oil seeds rainfed	
C_B_IRC – cane and beet irrigated	C_B cane & beet (disaggregated)
C_B_RFC – cane and beet rainfed	
PFB_IRC – plant fibres irrigated	PFB plant-based fibers (disaggregated)
PFB_RFC – plant fibres rainfed	
OCR_IRC – other crops irrigated	OCR other crops (disaggregated)
OCR_RFC – other crops rainfed	
LSTK – Livestock	CTL Cattle, OAP Animal products, RMK Raw milk, WOL wool
AGRO – Agriculture other	FRS forestry, FSH Fish
PCF – Processed food	OMT Meat products, VOL Vegetable oils, MIL Dairy products, PCR Processed rice, SGR Sugar, OFD Food products other, B_T Beverages and tobacco
M_M – Metals and minerals	NMM mineral products, I_S iron and steel, NFM non-ferrous metals, FMP metal products, OMN minerals
CHEM - Chemicals	CRP chemicals
PAP – Pulp and paper	PPP pulp and paper products
ENE - Energy	COA coal, OIL oil, GAS gas, P_C petroleum coal, ELY Electricity, GDT gas distribution, TnD Transmission and distribution
ELT – Electricity thermal	NuclearBL, CoalBL, GasBL, OilBL, OtherBL, GasP, OilP
ELN – Electricity non-thermal	WindBL, HydroBL, SolarP

RESCU sector	GTAP9Power sector
MANU – Manufacturing	TEX Textiles, WEA Wearing apparel, LEA Leather products, LUM Wood products, PPP Paper products, CMT cement MVH motor vehicles, OTN transport equipment, ELE electric equipment, OME machinery, OMF manufactures, WTR water
IWT – Industrial Water	WTR – Water distribution
MWT – Municipal Water	
SERV – Other services	OSG Public Administration, CMN Communication, OFI Financial services, ISR Insurance, OBS Business services, ROS Recreational services
TRNS – Transport	OTP Transport, WTP Water Transport, ATP Air transport
CONS – Construction	CNS Construction, DWE Dwellings

Table 4.6- RESCU-Water aggregation of GTAP-Power regions

RESCU region	**Preponderant thermal zone**	**Precipitation levels**	**TRWR/capita (m^3/year)**	**GTAP-Power regions**
AUZ Australia and New Zealand	Subtropical – warm	Medium	High (24,784)	Australia, New Zealand, Rest of Oceania
SEA – South East Asia	Tropical – warm	High	High (9,043)	Brunei, Cambodia, Indonesia, Laos, Myanmar, Philippines, Singapore, Thailand, Vietnam, Nepal, Rest of SE Asia
CNA- China	Temperate – cool	Medium	Medium/Low (2,185)	China, Hong Kong, Taiwan
NEA – North East Asia	Temperate – cool	High	Medium (2,835)	Japan, Korea Republic of, Rest of East Asia*

RESCU region	Preponderant thermal zone	Precipitation levels	TRWR/capita (m^3/year)	GTAP-Power regions
SAS – South Asia	Subtropical – warm	Medium	Low (1,556)	Bangladesh, Pakistan, Sri Lanka, Rest of South Asia*
IND – India	Tropical – warm/ subtropical – warm	Medium	Low (1,658)	India
CEA – Central Asia	Temperate – cool	Medium	High (7,689)	Mongolia, Kazakhstan, Kirgizstan
MEA – Middle East Asia	Subtropical – warm	Low	Low (1,592)	Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, UAE, Rest of Western Asia*
EUA – Eurasia	Boreal - cold	Medium	High (20,739)	Belarus, Russia, Ukraine, Rest of Eastern Europe, Rest of Former Soviet Union*, Armenia, Azerbaijan, Georgia
NEU – Northern Europe	Temperate – cool	Medium	High (5,195)	Belgium, Denmark, Estonia, Finland, Germany, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Sweden, Great Britain, Switzerland, Rest of EFTA*
SEU – Southern Europe	Temperate – cool /subtropical – warm	Medium	Medium (3,340)	Austria, Cyprus, Czech Republic, France, Greece, Hungary, Italy, Malta, Portugal, Slovakia, Slovenia, Spain,

RESCU region	Preponderant thermal zone	Precipitation levels	TRWR/capita (m^3/year)	GTAP-Power regions
				Albania, Bulgaria, Croatia, Romania, Rest of Europe*
NAF – Northern Africa	Subtropical – warm	Low	Low (1,014)	Egypt, Morocco, Tunisia, Rest of North Africa*, Rest of Eastern Africa*
CAFH – Central Africa	Tropical – warm	High	High (5,074)	Benin, Burkina-Faso, Cameroon, Cote d'Ivoire, Ghana, Guinea, Nigeria, Togo, South Central Africa*, Ethiopia, Kenya, Madagascar, Mauritius, Mozambique, Rwanda, Tanzania, Uganda
CAFD – Sahel	Tropical – warm	Low	High (12,155)	Rest of Western Africa*, Rest of Central Africa*, Senegal
SAF – Southern Africa	Subtropical – warm	Medium	Medium/Low (2,244)	Malawi, Zambia, Zimbabwe, Botswana, Namibia, South Africa, Rest of South African Customs Union*
NOA – Canada	Temperate – cool	Medium	High (90,854)	Canada, Rest of North America*
USA – United States	Subtropical – warm/cool / temperate – cool	Medium	High (7,060)	United States
NLAM – North Latin America	Tropical – warm	High	High (22,159)	Mexico, Bolivia, Columbia, Ecuador,

RESCU region	Preponderant thermal zone	Precipitation levels	TRWR/capita (m^3/year)	GTAP-Power regions
				Peru, Venezuela, Rest of South America*, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America*, Dominican Republic, Jamaica, Puerto Rico, Trinidad Tobago, Caribbean*
BRA – Brazil	Tropical – warm	High	High (44,105)	Brazil
SLAM – South Latin America	Subtropical – warm/ cool/temperate – cool	Medium	High (32,035)	Argentina, Chile, Paraguay, Uruguay, Rest of the World*

Note: (*) aggregated regions in the GTAP database

4.6. Summary

Starting from the research gaps revealed through the literature review in Chapter 3, this chapter described the overall advances to the economic analysis of global water scarcity to be made throughout this thesis. The answers to the three sets of research questions will be provided in Chapter 6-8 through the use of a global CGE modelling framework (RESCU-Water) developed for this purpose. The first two research questions emphasise the importance of irrigation water uses for the future state of demand-driven water stress. The evolution of irrigation water requirements will thus be analysed in relation to socioeconomic development and to climate change incidence over crop water productivity. The third research question refers to the economy-wide impacts of demand-driven water scarcity and thus also requires the consideration of non-crop water uses.

The RESCU-Water model introduces a detailed specification of water inputs across economic activities and households. Thus, a clear distinction is made between water as an endowment used by self-abstracting sectors and water as a commodity supplied through distribution networks. This separation allows for a separate accounting of the costs of water supply (water as a commodity) and the water scarcity value applicable to regions where total unconstrained demand exceeds sustainable supply (water as a scarce natural endowment). The introduction of water as endowment also enables the consideration of alternative water management options by taking into account allocation possibilities based on differences between endogenous water productivities of users. These water allocation regimes and their implementation in the RESCU-Water framework are explored in Chapter 8.

The production functions of economic sectors are detailed to cover the specifics of water uses across five self-abstracting industries (irrigated crops, livestock, thermal power, industrial water supply and municipal water supply) and supplied economic activities (water-intensive and non-water intensive industries). This advanced specification of substitution possibilities between water-related inputs (water endowments and supplied water) and other inputs enables the consideration of differences in adaptation to water scarcity at a sectoral level based on market price signals. Adaptation is further enabled through the substitution between varieties of the same commodity having different water productivities – rainfed and irrigated varieties for crops, and thermal and non-thermal technologies for power production.

RESCU-Water also introduces important advances in crop production specification using a CGE framework. Crops systems are described using a “bottom-up” approach through a separation of irrigated and rainfed technologies and land types. Furthermore, a distinction is made between irrigation infrastructure and water inputs in irrigated production to better account for withdrawal limits in water scarcity scenarios. As opposed to most global CGE models focusing on water use in agriculture, irrigation supply is endogenised to follow the evolution of market prices under socioeconomic development, climate change and water scarcity simulations.

Chapter 5. Extending the GTAP database for global water analyses

5.1. Rationale

As reviewed in Chapter 3, the GTAP database has so far underpinned all global CGE water modelling. Nevertheless, the lack of detail over water uses in economic activities in GTAP has led to model-specific modifications to the data structure being made in order to have a better representation of water as an input to production. Most efforts have been dedicated to the identification of irrigation as a factor of production serving as a proxy for water uses in agriculture. Within this strand of work, there were several approaches to determining the added-value of irrigation in crop output as this factor is not separately detailed in the GTAP data.

Less has been done, notably in the past decade, for the integration of water uses outside irrigated crop production in one modelling framework. From a data standpoint, the only two models to do an economy-wide mapping of water uses (FARM in Darwin et al. 1995 and GTAP-W1 in Berrittella et al. 2007) were limited in explaining the structure of demand for water as a physical resource from two perspectives – a lack of water volumetric use data and a low level of detail regarding the water use structure. For the former, in the FARM model water was embedded only in monetary terms, making it impossible to impose withdrawal limits based on volumetric sustainability targets. For the latter, in both models, water use outside agriculture was bundled in one single sector – services for the FARM model and water distribution for GTAP-W1. This lack of disaggregation overlooked to a large extent the heterogeneity in terms of water productivity and adaptability to water deficits of water users across industries (among which some are self-abstracting sectors), services and households. Since the development of these two models, some progress has been made in detailing water uses for which data is now available for a large number of economies through the EXIOPOL project (Tukker et al. 2013).

The changes to the GTAP database for the RESCU-Water model tackle two issues. The first is related to the data requirements for crop production modelling. This implies the separation of production activities for rainfed and irrigated crops. For irrigated production, the value added of irrigation also needs to be dissociated from other inputs and this is done using an improved method relative to those used for GTAP-W2 (Calzadilla et al. 2011a) and GTAP-BIO-W (Haqiqi et al. 2016). The second issue regards the requirement for more detail on the physical water uses across sectors. The GTAP database is thus extended with water accounts for five classes of self-abstracting activities – irrigated crops, livestock, thermal power, municipal water and industrial water supply. As a further step, the water supply sector in the GTAP database is also split to account separately for the industrial and municipal water intensities. This separation is also important in establishing water demand baselines in which the two water varieties have different dynamics related to socioeconomic development.

5.2. Disaggregation of GTAP crop production sectors

The GTAP database comprises a reasonable level of detail regarding cropping activities through a distinct representation of production technologies of eight crop classes - *rice* (pdr), *wheat* (wht), *other grains* (gro), *veg&fruits*(v&f), *oil seeds* (osd), *cane&beet* (c_b), *fiber plants* (pfb) and *other crops* (ocr). Nevertheless, for the introduction of water and irrigation as explicit factors of production for crops a further division of production into the rainfed and irrigated typologies is required. In the RESCU-Water database accounting, this separation is obtained in two steps. First, total output by crop class is split using external data which differentiates crops between the two varieties. Second, the value added for irrigation in the base year is calculated starting from yield losses derived from crop modelling in scenarios where global irrigation use is disabled.

5.2.1. Disaggregation of rainfed and irrigated crop output

The division of crop output is done through the use of output shares $\alpha_{crop,m,r}$ for each growing method *m* calculated on a monetary basis:

$$\alpha_{crop,m,r} = \frac{vom_{crop,m,r}}{\sum_m vom_{crop,m,r}} \tag{5.1}$$

where $vom_{crop,m,r}$ is the value of output by crop and by growing variety calculated at market prices. The $\alpha_{crop,m,r}$ are then used with the SplitCom tool (Horridge 2005) to disaggregate the GTAP crop production. Similarly to Haqiqi et al. (2016), through this simple output-based split, it is assumed that the production structure of the two methods for non-land inputs is identical.

Rainfed and irrigated crop production figures are not available through global crop statistics, therefore data regarding the output by variety is taken from estimates obtained through the Global Crop Water Model (GCWM, see Siebert & Döll 2010a). GCWM uses the MIRCA2000 cropping maps (Portmann et al. 2010) which distinguish between 29 crop types and evaluates rainfed and irrigated production by combining national and sub-national statistics for areas and yields with remote sensing data. Furthermore, GCWM, as a crop simulation model (Siebert & Doll 2008), also enables the calculation of green and blue water consumption occurring through crop evapotranspiration by considering cropping patterns, climatic conditions and soil water balances. The model also has the capacity to determine yield losses on irrigated land when irrigation is disabled. The advantage of employing GCWM comes thus from the opportunity of using a coherent dataset covering yields, acreage and irrigation water intensities under scenarios with and without irrigation use.

As GCWM is run over the years 1998-2002, the yield and the implicit production values are updated to the 2004 RESCU-Water base year by factoring in crop-specific annual yield improvements due to technological change. This information is taken from the IMPACT model (Nelson et al. 2010) and distinguishes between the rainfed and irrigated varieties.

For the *vom* output calculation required for equation (5.1), the updated GCWM output expressed in physical units is converted to monetary values by multiplying the crop output with representative FAO prices. The GCWM crops classes are then mapped to the eight crop classes in GTAP (see mapping in Table 5.1). The $\alpha_{crop,m,r}$ shares are then used to split the GTAP database.

Table 5.1 - GCWM to GTAP crop mapping

RESCU crop class	**GCWM crop class**
PDR – paddy rice	Rice
WHT – wheat	Wheat
GRO – other grains	Maize, Barley, Rye, Millet, Sorghum
V_F – vegetables and fruits	Potatoes, Cassava, Groundnuts, Citrus, Date palm, Grapes, Other perennial
OSD – oil seeds	Soybeans, Sunflower, Oil palm, Rapeseed/canola
C_B – cane and beet	Sugar cane , Sugar beet
PFB – plant fibres	Cotton
OCR – other crops	Pulses, Cocoa, Coffee, Others annual
Not mapped	Managed grassland, Maize forage, Rye forage, Sorghum forage

The production weights obtained at the output of SplitCom[10] and aggregated to the RESCU-Water regions are presented in Table 5.2. From the results, it can be seen that many regions have a high reliance on irrigated crop production. As expected, paddy rice is produced predominantly on irrigated land. Fibers and sugar cane (*cane&beet*) are also mainly produced through irrigation. Water-challenged regions (Middle East and Northern Africa, South Asia) are

[10] It should be noted that the weights instructed as input for Splitcom may be slightly different that those obtained at the output. This is due to adjustments made by the tool in order to produce a balanced database.

largely dependent on irrigation, with at least half of production coming from irrigated land for most crops.

Table 5.2 - Irrigated production weight in total production - by crop type

RESCU-Water region	Rice	Wheat	Other grains	Veg& fruits	Oil seeds	Cane& beet	Fibers	Other crops
Australia &NZ	92%	3%	18%	76%	0%	72%	96%	18%
China	89%	71%	52%	21%	30%	28%	41%	18%
Northeast Asia	88%	42%	28%	25%	20%	50%	0%	12%
Central Asia	96%	14%	53%	77%	41%	72%	90%	96%
Southeast Asia	58%	61%	8%	7%	3%	72%	7%	20%
South Asia	98%	97%	71%	64%	52%	94%	99%	98%
India	70%	91%	22%	30%	18%	91%	45%	17%
Canada	0%	6%	5%	27%	2%	0%	0%	3%
USA	97%	25%	20%	83%	12%	46%	59%	67%
South Latin Am	85%	10%	14%	63%	3%	65%	18%	51%
North Latin Am	59%	27%	24%	47%	3%	63%	78%	33%
Brazil	53%	3%	3%	11%	3%	10%	8%	24%
Southern Europe	96%	5%	27%	33%	33%	34%	96%	43%
Northern Europe	0%	2%	2%	24%	0%	14%	0%	10%
Eurasia	47%	11%	11%	7%	3%	12%	80%	19%
Middle East	98%	47%	53%	54%	66%	85%	99%	78%
Northern Africa	97%	35%	43%	76%	80%	99%	97%	67%
Central Africa	16%	9%	2%	3%	3%	38%	7%	5%
Sahel	63%	99%	1%	9%	0%	60%	11%	7%
Southern Africa	52%	47%	5%	81%	32%	54%	42%	38%

5.2.2. Irrigation valuation

The second step is to separate the contribution of irrigation in the value added of irrigated crop output. Similarly to GTAP-W2 and GTAP-BIO-W, this is done by deducting the value of irrigation infrastructure from the value of land inputs going into irrigated production. As irrigation is used to improve crop growing conditions and leads thus to better yields, it can be inferred that this facility has an incremental effect on rents paid for land use.

The previous models determined the value of irrigation based on differences in land rents between irrigated and rainfed land. In GTAP-BIO-W, rents were calculated as the ratio between land endowment inputs into each growing method and the corresponding acreage. Due to the identical cost structure of irrigated and rainfed production, the differences between rainfed and irrigated land rents implicitly corresponded to differences in yields between the two land types. In GTAP-W2, as production was not split into the two growing methods, yield information was directly used as an indicator of land rent differences.

The underlying assumption for both models was that in the absence of irrigation, yields on irrigable land would return to values obtained for rainfed crops in the considered growing unit (macro-region for GTAP-W2, AEZ for GTAP-BIO-W). In the irrigation water accounting framework for the RESCU-Water model, this assumption is challenged. In many instances, the practice of irrigation takes place on land that is endowed with different growing conditions compared to the rainfed type within the same region. To reveal this, the GCWM data for the 'no irrigation' scenario is used[11]. This enables the calculation of yields at a 0.5° resolution by taking climatic and natural soil moisture conditions into account.

Figure 5.1A confirms that yields on irrigated land using irrigation are superior to rainfed land in most cases. However, in the 'no irrigation' scenario, yields on irrigable land rarely return to values similar to those on rainfed land (Figure 5.1B), with the majority of cases leading to both poorer and better yield results.

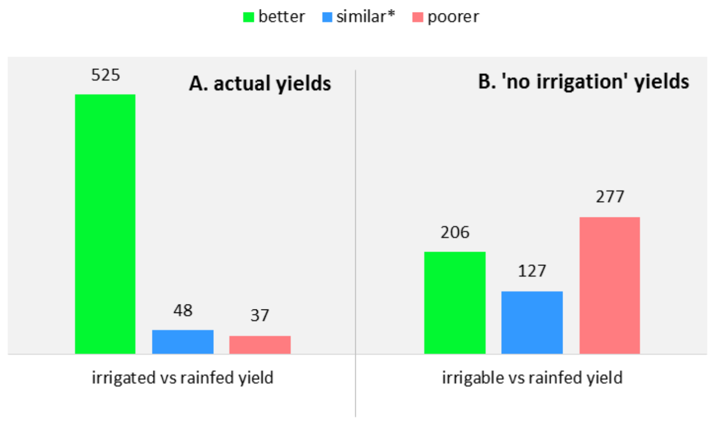

Figure 5.1 - Yield comparison of irrigated and rainfed land across GTAP regions and crop classes

Note: (*) yields differing by no more than ±5%. GCWM yields for the two scenarios (actual and 'no irrigation') mapped onto the eight GTAP crop classes and 140 regions. In 510 out of 1120 cases, either one or both growing methods were absent at the GTAP regional level making the comparison impossible

As an improvement to the previous methods, the value of irrigation for each GTAP crop class is calculated as the share $\beta_{crop,r}$ of land payments equal to the ratio of production losses of "no irrigation" to total actual irrigated production (equation (5.2)). Rents paid to irrigation $evfa_r^{Irrigation}$ and irrigated land $evfa_r^{IrrLand}$ are separated in equations (5.3) and (5.4). In addition, land rents entering the cost structure of rainfed crops are requalified as rainfed land rents (equation (5.5)). Total supply of each of the three new factors is calculated through equations (5.6)-(5.8) by summing up all rents paid by the individual cropping activities.

$$\beta_{crop,r} = \frac{losses_{crop,irrigated,r}}{vom_{crop,irrigated,r}} \tag{5.2}$$

$$evfa_r^{Irrigation} = \beta_{crop,r} * evfa_{crop,irrigated,r}^{land} \tag{5.3}$$

[11] Yield and production levels for the GCWM "no irrigation" scenarios were obtained through personal communication with Dr. Stefan Siebert

$$evfa_r^{IrrLand} = (1 - \beta_{crop,r}) * evfa_{crop,irrigated,r}^{land} \tag{5.4}$$

$$evfa_r^{RfLand} = evfa_{crop,rainfed,r}^{land} \tag{5.5}$$

$$evoa_r^{irrigation} = \sum_{crop} evfa_{crop,irrigated,r}^{Irrigation} \tag{5.6}$$

$$evoa_r^{IrrLand} = \sum_{crop} evfa_{crop,irrigated,r}^{IrrLand} \tag{5.7}$$

$$evoa_r^{RfLand} = \sum_{crop} evfa_{crop,rainfed,r}^{RfLand} \tag{5.8}$$

Figure 5.2 compares the weights of irrigation in total irrigated crop costs across the two irrigation valuation principles. By using the 'no irrigation' production losses the RESCU-Water database, the value of irrigation in most regions is larger than that obtained using the GTAP-W/GTAP-BIO-W accounting principle, with the share of irrigation in irrigated crop output for water-scarce regions (South Asia, India, Middle East and Northern Africa) being considerably greater. At the same time, in some areas, the actual irrigated yield values are consistently inferior to those on rainfed land. Thus, applying the valuation principle from the other two GTAP-based models leads to a negative value added of irrigation i.e. yields are improved when irrigation is not used. Therefore, in Canada, the comparison of results using the two valuation methods is not even possible.

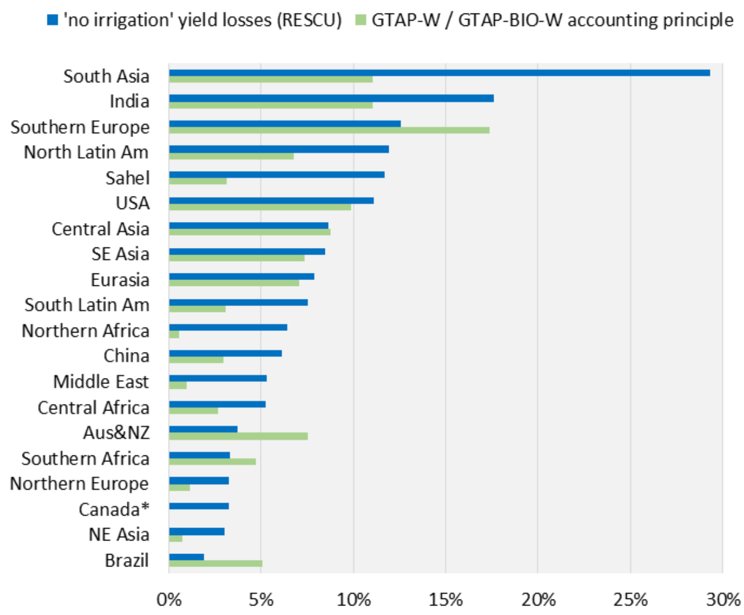

Figure 5.2 - Value share of irrigation in irrigated crop costs – comparison of accounting principles

*Note: *negative values obtained for irrigation using the GTAP-W accounting principle*

Starting from this base year valuation of irrigable and rainfed land, a conversion of these two land types is possible in model simulations given the two-step land supply specification. In a first step, total arable land supply follows a logistic function calibrated for an initial land supply elasticity similar to that found in the literature (see Section 4.4.4.2). In the second step, arable land is attributed to the rainfed and irrigable land types[12] through a CET function. Given the lack of empirical evidence regarding the convertibility of rainfed land into irrigable land, a value of 2 is assumed for the transformation elasticity σ_{AL}.,a value considerably lower than that used in Taheripour et al. (2013a) where the elasticity takes a values of 10. Considering the importance of this parameter in model results, two sensitivity analyses are conducted for σ_{AL} in Chapter 6 (Section 6.5.3) and in Chapter 8 (Section 8.4.1.6).

The land conversion is nevertheless dependent on the evolution of land yields in the 2004-2050 simulation horizon. For the model baseline, yield differences between the two land types for every region are driven by yield improvements as determined from the IMPACT model dataset (Nelson et al. 2010). Therefore, a marked shift from the base year equilibrium towards the use of more irrigable land is not obtained unless the yield growth differentials are significant. The yield values used are presented in Table A1 in Annex A – the yield differences show that irrigable land can both outperform and underperform rainfed land depending on the region and crop type.

5.3. Economy-wide water accounting

This section explains how physical water uses are despatched to the different user types by expanding the GTAP data with water accounts. As described in Chapter 4, the RESCU-Water model makes a distinction between water as endowment used by self-abstracting sectors and water as a commodity supplied through distribution networks. As an endowment, water is a raw natural resource used by self-abstractors directly into their activity. As a commodity, water is treated pre- and post-use, and distributed to industries, services and households, and therefore requires a standalone activity with a specific production technology to supply it. This sector is already represented in the GTAP database through the *wtr* water distribution sector.

The economy-wide water accounting implies attaching volumetric water uses to self-abstracting industries. For supplied users, the mapping of to the monetary flows of the GTAP *wtr* sector

[12] Referring to the FAO terminology which distinguishes between irrigated land (land effectively irrigated) and irrigable land (land equipped with irrigation), in the RESCU-Water model the composite of irrigable land and irrigation relates to land effectively irrigated. Thus, there is no separate consideration of land equipped with irrigation but managed as rainfed land.

enables the tracking of demand of water as a commodity by the downstream users. Furthermore, to better qualify the differences between supplied users in water use projections, the *wtr* distribution sector is split into the municipal and industrial water supply sectors. The starting assumption in the RESCU-Water framework is that water scarcity cannot be currently identified through specific water rents in a global economic database. Therefore the inclusion of volumetric data to self-abstracting industries is an environmental extension of the input-output GTAP data and does not change the base year structure or values of monetary flows.

5.3.1. Water accounting of self-abstracting sectors

The self-abstracting sectors are divided into five classes – irrigated crops, livestock, thermal power, municipal water supply and industrial water supply. Water use data for irrigated crops are taken from the GCWM model. For the other sectors, the WaterGAP water data (Flörke et al. 2013) published through the EXIOBASE2 input-output database (Wood et al. 2014) is used. Although EXIOBASE makes available water consumption also for crops with calculations done by the LPJmL crop model (Rost et al. 2008), to preserve the consistency with the irrigation valuation work presented above, the GCWM model data is preferred. Water uses are considered as withdrawals (Table 5.3) with the exception of livestock for which consumption values are employed due to the absence of withdrawals data for this category.

Table 5.3 - Water use types and data sources

Self-abstracting sector	Use type	Data source
Irrigated crops	Withdrawals	Consumption from Siebert & Döll (2010) Irrigation efficiency through Rohwer et al. (2007)
Livestock	Consumption	WaterGAP (Flörke et al. 2013) through EXIOBASE2 (Wood et al. 2014)
Thermal power	Withdrawals	
Industrial water supply		
Municipal water supply		

5.3.1.1. Crop blue water uses

The calculation of water withdrawals for crops relies on the GCWM water consumption data (Siebert & Döll 2010) combined with the regional irrigation efficiencies calculated using data from Rohwer et al. (2007).

GCWM uses the Penman-Monteith approach (Allen et al. 1998) to calculate the reference evapotranspiration for each crop type. It then determines the annual blue water consumption required through irrigation as the difference between this reference value and the actual evapotranspiration given soil moisture naturally contained by irrigated land. The resulting consumption values are thus equal to the volumes of blue water required to compensate for soil moisture deficiency and which lead to optimal plant growth given the other climatic conditions.

Irrigation efficiencies are determined at a country level and then aggregated to the RESCU-Water regions. The values are a function of conveyance, distribution and field application technologies. Following the method in Rohwer et al. (2007), each country is assigned to an Irrigation Functional Type (IFT) which characterises the preponderant field application methods (surface, sprinkler, micro or mixed), with each having a different composite application efficiency (EA). Next, Rohwer et al. (2007) determine an overall conveyance efficiency (EC) based on the IFT attribution. Last, the distribution efficiency is included through a management factor (MF) which considers the type of distribution (open or pressurised) and the size of surface and mixed irrigation systems (small, large and extended). Since the final irrigation efficiencies are not made available in Rohwer et al. (2007), these are calculated as the product of the three components in equation (5.9), with country data taken from the study.

$$\eta = EA * EC * MF \tag{5.9}$$

Table 5.4 – Regional irrigation efficiencies and withdrawals by crop class for 2004

RESCU-Water region	η_r	*Withdrawals (km³)*								
		Total	Rice	Wheat	Other grains	Veg& fruits	Oil seeds	Cane& beet	Fibers	Other crops
Australia &NZ	47.9%	14.6	1.8	0.5	0.7	2.3	-	3.4	4.5	1.4
China	38.8%	372.5	209.1	62.3	53.8	19.0	13.2	3.3	7.7	4.3
Northeast Asia	39.3%	9.1	8.2	0.0	0.2	0.3	0.1	0.0	-	0.2
Central Asia	40.3%	72.8	4.5	4.8	6.3	7.7	0.1	0.5	42.1	6.8
Southeast Asia	38.3%	197.0	157.4	10.6	1.8	9.8	0.9	11.7	0.2	4.6
South Asia	40.1%	301.3	60.2	118.6	13.1	14.0	1.6	25.2	42.1	26.4
India	45.0%	599.6	208.5	190.3	15.2	32.6	16.9	78.8	28.6	28.8
Canada	53.6%	2.2	-	0.6	0.4	0.2	0.5	-	-	0.5
USA	57.6%	158.4	17.7	12.0	46.6	26.7	18.6	3.3	24.7	8.7
South Latin Am	39.3%	20.3	3.0	0.9	1.5	9.9	0.6	1.5	0.4	2.6
North Latin Am	40.4%	95.1	11.1	10.7	13.2	29.0	1.0	18.3	2.8	9.1
Brazil	68.8%	10.7	4.6	0.0	0.1	2.5	0.1	1.8	0.1	1.4
Southern Europe	55.3%	66.3	3.9	1.9	12.6	27.6	3.0	2.1	5.3	9.9
Northern Europe	62.6%	1.0	-	0.0	0.0	0.5	-	0.2	-	0.2
Eurasia	57.4%	20.1	1.4	6.1	4.6	2.9	0.2	0.8	1.0	3.0
Middle East	42.3%	239.8	18.7	39.8	18.5	85.9	3.0	10.1	20.1	43.7
Northern Africa	43.2%	166.1	16.0	23.0	24.7	46.6	1.2	11.7	7.7	35.1
Central Africa	45.1%	16.0	7.5	0.1	0.9	1.9	0.1	1.8	0.7	3.0
Sahel	38.5%	8.1	4.6	0.2	0.3	1.2	-	0.8	0.1	0.9
Southern Africa	61.3%	11.4	0.1	1.7	0.8	3.3	0.2	2.4	0.9	2.0
World		**2,382.1**	**738.3**	**484.2**	**215.1**	**323.9**	**61.4**	**177.8**	**188.8**	**192.7**

Table 5.4 presents the results of withdrawal calculations aggregated for the RESCU-Water regions. Total withdrawals in the base year 2004 are 2382 km^3. This value is lower than the 2716

km³ estimates in Alexandratos & Bruinsma (2012) for 2007, but because it considers water requirements exclusively for optimal crop growth, it does not include the additional water required for paddy rice flooding as in the FAO study. The most water-intensive activities are *rice* in China, India and Southeast Asia, and *wheat* in India and South Asia. *Veg&fruits* in the Middle East and *cane&beet* in India are also important irrigation water users.

5.3.1.2. Non-crop blue water uses

Water uses outside crop production are taken from EXIOBASE. The second version of the database updates the environmental accounting to 2007 structured around 44 world regions (43 countries and one rest of the world). Water data for non-crop users is taken from the calculations done in Flörke et al. (2013) using the WaterGAP model. The WaterGAP data differentiates between water consumption and withdrawals and is structured in four main user categories – livestock, manufacturing, thermal electricity production and domestic.

Water withdrawals of the WaterGAP categories are mapped to the corresponding self-abstracting sectors in the RESCU-Water framework – livestock, industrial water supply (manufacturing), thermal power and municipal water supply (domestic). To determine withdrawals at a GTAP regional-level for the year 2004, the following procedure is employed:

- The GTAP9-Power database with 2007 as base year is aggregated to match the regions and the base year in EXIOBASE
- A regional blue water intensity *bwi* is calculated for all the self-abstracting sectors *sai*. This calculation is done by mapping the EXIOBASE withdrawals to the monetary output derived from the GTAP9 database for the year 2007 (equation (5.10)):

$$bwi_{sai} = \frac{Withdrawals_{sai}^{EXIOBASE}}{Output\ value_{sai}^{GTAP}} \tag{5.10}$$

- The intensity values *bwi* are applied to the 140 GTAP9 regions for 2004 to determine the base year regional water uses by sector

Table 5.5 shows the resulting regional withdrawal levels by self-abstracting sector in the RESCU-Water data.

The assignment of EXIOBASE manufacturing withdrawals to RESCU-Water industrial water supply and not to individual sectors implies that industrial water is a homogenous good among industries. It also reflects that water is distributed and not abstracted by downstream sectors. Although the WaterGAP manufacturing water uses are disaggregated in EXIOBASE to industrial sub-sectors[13], mapping these to the GTAP sectors leads to inconsistencies in terms of water intensities (\$ supplied water / m^3 supplied water). Table 5.6 lists all the GTAP sectors with inputs from the *wtr* sector and shows their weights in the *wtr* output. Compared to the industrial water use weights determined through EXIOBASE data, only the chemicals and the manufactures sectors shows a good correspondence. Interestingly, EXIOBASE does not account for any withdrawals by the energy sectors.

Table 5.5 – RESCU-Water withdrawals by self-abstracting sector for 2004 (km^3)

RESCU-Water region	Total	Municipal supply	Industrial supply	Thermo-electric	Livestock	Irrigated crops
Australia &NZ	**25.9**	5.7	3.7	0.9	1.0	14.6
China	**511.7**	36.0	44.1	56.1	3.0	372.5
Northeast Asia	**56.2**	23.1	14.8	8.9	0.3	9.1
Central Asia	**89.1**	2.7	3.3	10.0	0.3	72.8
Southeast Asia	**276.3**	19.1	19.5	39.6	1.1	197
South Asia	**316.2**	6.8	2.6	5.3	0.2	301.3
India	**662.9**	20.7	30.7	10.0	2.0	599.6
Canada	**40.3**	4.2	3.8	29.9	0.3	2.2
USA	**451.6**	46.5	42.7	201.9	2.1	158.4
South Latin Am	**37.4**	5.2	1.9	9.6	0.5	20.3
North Latin Am	**137.6**	17.7	10.4	12.8	1.7	95.1
Brazil	**27.8**	5.3	5.6	4.7	1.5	10.7
Southern Europe	**158.7**	19.4	17.9	54.0	1.1	66.3
Northern Europe	**88.0**	16.5	17.5	51.7	1.3	1
Eurasia	**79.7**	9.7	6.7	42.3	0.9	20.1
Middle East	**402.1**	100.9	23.0	37.1	1.4	239.8
Northern Africa	**172.0**	3.1	1.4	0.0	1.4	166.1
Central Africa	**23.7**	4.1	2.7	0.0	0.9	16
Sahel	**9.3**	0.6	0.4	0.0	0.2	8.1
Southern Africa	**17.6**	3.9	1.7	0.3	0.4	11.4
World	**3,584.2**	**351.1**	**254.2**	**574.9**	**21.5**	**2,382.1**

[13] The disaggregation of WaterGAP data is only briefly explained by the authors in Lutter et al. (2013)

Table 5.6 - GTAP industrial water users

GTAP sector	**Description**	**% of *wtr* output value (GTAP)**	**% of EXIOBASE industrial withdrawals**	**EXIOBASE industrial withdrawals (mm³)**
crp	Chemical, rubber, plastic products	27.9%	28%	88,073
ome	Machinery and equipment nec	27.3%	6%	19,985
mvh	Motor vehicles and parts	8.6%	3%	7,997
fmp	Metal products	6.8%	8%	23,990
nmm	Mineral products nec	5.3%	3%	10,119
p_c	Petroleum, coal products	4.5%	0%	-
i_s	Ferrous metals	3.5%	18%	58,078
ppp	Paper products, publishing	3.0%	11%	35,472
ele	Electronic equipment	2.3%	1%	2,248
gas	Gas	2.2%	0%	-
omf	Manufactures nec	1.8%	2%	7,525
nfm	Metals nec	1.7%	1%	2,561
lum	Wood products	1.6%	0%	-
omn	Minerals nec	0.9%	0%	-
wap	Wearing apparel	0.7%	1%	4,132
coa	Coal	0.5%	0%	-
ofd	Food products nec	0.3%	4%	12,757
b_t	Beverages and tobacco products	0.2%	1%	3,403
tex	Textiles	0.2%	4%	12,427
otn	Transport equipment nec	0.2%	1%	1,725
oil	Oil	0.1%	0%	-
lea	Leather products	0.1%	1%	3,165
mil	Dairy products	0.1%	1%	3,299
sgr	Sugar	0.1%	1%	4,097
vol	Vegetable oils and fats	0.0%	0%	-
omt	Meat products nec	0.0%	2%	7,768
cmt	Bovine meat products	0.0%	1%	2,159
pcr	Processed rice	0.0%	1%	3,183

5.3.2. Disaggregation of the GTAP water sector

To split the *wtr* sector in GTAP into industrial and municipal water distribution the SplitCom tool is used once more. The split proportions required by the tool (inputs to other sectors, cost structure and own demand) are calculated through a GAMS script by using a set of assumptions as detailed below.

For the domestic variety of the *wtr* commodity as an input to other sectors and as a final demand good, the monetary values assigned to one of the two water distribution types is based on the mapping of the disaggregated GTAP sectors represented in Table 5.7. In addition, the final demand component (households, government and investment) is attributed to the output of municipal water distribution.

For the foreign variety of *wtr,* the physical amounts of internationally traded bulk water (excluding thus beverages) are considered negligible and are not accounted for. For instance, total traded volumes in 2007, the base year for the EXIOBASE data, amounted to 923 Mm^3 in 2007 according to the COMTRADE database, or about 0.1% of total withdrawals of non-agricultural users (as calculated from EXIOBASE), out of which 782mm^3 were traded between China, Hong Kong and Macau. Hence the exchange of important physical quantities is not representative at a global level but is more characteristic to a small number of local cases. At the same time, the GTAP monetary values of *wtr* trade flows are concentrated between European countries and the USA (representing 1% of global output of the *wtr* sector) and are thus not reflective of the EXIOBASE physical volumes. Therefore, in the splitting of the *wtr* sector, all the GTAP flows related to the foreign variety are exclusively attributed to a residual water trade *twt* sector which is not considered to have a water use component attached. This sector is further on combined with the services sector in the RESCU-Water database aggregation.

Table 5.7 - Mapping of GTAP sectors by water distribution type

Water distribution	**GTAP sectors**
Industrial (iwt)	rice, wheat, other grains, veg&fruits, oil seeds, cane&beet, plant fibers, other crops, cattle, animal products, raw milk, wool, forestry, fishing, coal, oil, gas, minerals, bovine meat, other meat, oils, dairy, processed rice, sugar, other food products, beverages and tobacco, textiles, wearing apparel, leather products, wood products, paper products, petroleum coal, chemicals, ferrous metals, non-ferrous metals, metal products, motor vehicles, transport equipment, electronic equipment, other machinery, manufactures, electricity, gas distribution, construction
Municipal (mwt)	trade, transport, water transport, air transport, communication, financial services, insurance, business services, recreational services, public administration, dwellings +households, government, investment

The cost shares α_i to split the *wtr* costs across the three new sectors *i* (iwt, mwt, twt) are calculated based on the ratio between the outputs of the new sector and the initial *wtr* sector:

$$\alpha_i = \frac{vom_i}{vom_{wtr}} \tag{5.11}$$

with output values *vom* of the resulting sectors calculated as follows:

$$vom_{iwt} = \sum\nolimits_{industrial} vdfm_{wtr,industrial} \tag{5.12}$$

$$vom_{mwt} = \sum\nolimits_{services} vdfm_{wtr,services} + vdfm_{wtr,CGDS} + vdgm_{wtr} + vdpm_{wtr} \tag{5.13}$$

$$vom_{twt} = \sum\nolimits_{destination} vxmd_{\ wtr,destination} \tag{5.14}$$

where *vdfm*, *vdgm*, *vdpm* are the value of domestic sales at market prices by firms, government and households respectively, whereas v*xmd* is the value of exports by destination region.

Table 5.8 presents the resulting water productivities of the industrial and municipal water supply sectors throughout the RESCU-Water regions. These values calculated as \$ of output / m^3 can be interpreted as the cost of supply across the two user types. Generally, municipal water supply has a higher cost with values up to four times higher than that for industrial supply as in e.g. USA.

Table 5.8 - Municipal and industrial water productivities (\$ output / m^3)

Region	Municipal	Industrial
Australia &NZ	1.01	0.34
China	0.20	0.07
Northeast Asia	1.23	0.46
Central Asia	0.14	0.05
Southeast Asia	0.11	0.05
South Asia	0.12	0.05
India	0.08	0.02
Canada	0.18	0.04
USA	1.91	0.48
South Latin Am	0.30	0.07
North Latin Am	0.20	0.08
Brazil	1.10	0.39
Southern Europe	1.25	0.48
Northern Europe	1.45	0.44
Eurasia	0.84	0.20
Middle East	0.13	0.07
Northern Africa	0.25	0.17
Central Africa	0.27	0.19
Sahel	0.27	0.18
Southern Africa	0.62	0.39

5.4. Regional water resource base

The calculation of water availability at a regional level is important in determining the pressure exerted by specific user types. It also informs the upper withdrawal limits in the interest of ensuring long-term sustainable water use. In the RESCU-Water simulations but also generally, in all other global water modelling efforts, it is the total renewable water resources (TRWR) component that is taken as a reference level. TRWR is typically calculated from an administrative perspective by taking country boundaries into account. It is thus a measure of both internal resources (IRWR) coming from land precipitation and external through river inflow from neighbouring countries.

To avoid the possible double-counting by summing up the country-level TRWR values to a macro-regional level, resources were determined for each RESCU-Water region by taking into account the country IRWR values and the inflows between countries from different regions (Table 5.9). An adjustment to the inflows in South Asia was made by the including only the volumes guaranteed through the Indus Treaty between India and Pakistan and not the considerably larger inflows of the three rivers going into Pakistan.

Table 5.9 - TRWR calculation for RESCU-Water regions (km^3)

Region	**Quantity values considered**	**Quantities**
Canada	TRWR	2902
USA	TRWR / Alaska not considered	2089.4
Northern Latin America	IRWR + inflows: USA -> Mexico 5.4 km^3	6937.5 +5.4 **=6942.9**
Brazil	TRWR	8233
South Latin America	IRWR + inflows: Brazil → Paraguay 73.3 km^3 Brazil → Argentina 442.5 km^3 Brazil → Uruguay 70 km^3 Bolivia → Argentina 10.1 km^3 Bolivia → Paraguay 5.9 km^3	1269.2 +601.8 **=1871**
Northern Europe	IRWR	1299.9
Southern Europe	IRWR + total inflows France 25.2 km^3 Italy 8.8 km^3 Austria 22.7 km^3	873.6 +56.7 = **930.3**
Northern Africa	IRWR + total inflows: Sudan 119 km^3	97.3+ 119 =**216.3**
Sahel	IRWR[1]	**1039.2**
Central Africa	IRWR[1]	**2624.7**
Southern Africa	TRWR for Zambia 105.2 km^3 IRWR for other + total inflows: Angola → Namibia 10 km^3	105.2+ 89.6+ 10 =**204.8**
Middle East	IRWR + total inflows: Southern Europe → Turkey 3.5 km^3 Afghanistan → Iran 6.7 km^3	411+ 10.2 =**412.2**
Central Asia	IRWR + total inflows: Russia → Kazakhstan 9.2 km^3 China → Kazakhstan 21.5 km^3 China → Kyrgyzstan 0.5 km^3 Iran → Turkmenistan 1.1 km^3	411+ 32.3 = **443.3**
Eurasia	IRWR + total inflows: China → Russia 119 km^3 Turkey → Armenia 9.9 km^3	4511.6+ 128.9 = **4640.5**
South Asia	IRWR for Pakistan TRWR for Afghanistan + total Pakistan inflows: 170 km3 (Indus Treaty)	55+ 65+ 170 = **290**
India	TRWR	**1896.7**
Southeast Asia	IRWR + total inflows: China → Southeast Asia 217.8 km^3 India → Bangladesh 1121.6 km^3	5349.2+ 1339.4 =6778.6
China	TRWR	2896.6
Northeast Asia	TRWR	561.85
Australia and New Zealand	TRWR / Rest of Oceania excluded	819
Total		**42020.35**

5.5. Summary

The modifications to the GTAP database presented in this chapter support the data requirements and the data structuring required by the RESCU-Water model specification as detailed in Chapter 4. These changes implied a further detailing of productive sectors important for freshwater withdrawals (crops and water distribution sectors) and the addition of water use accounts to the model base year data.

In order to support the "bottom-up" representation of crop production, the monetary data of each of the eight GTAP crop classes was split to account for the rainfed and irrigated methods as separate productive activities. This disaggregation was done using production data from the spatially-detailed GCWM global crop model. Yield loss information under a 'no irrigation' scenario obtained from this model also enabled the introduction of a new valuation method for the irrigation infrastructure as an improvement relative to the previous attempts to isolate the contribution of irrigation to crop output (GTAP-W2 and GTAP-BIO-W).

The GTAP *wtr* water distribution sector was also separated into municipal and industrial supply with a view to capture the differences in water use intensities and supply costs across these two categories. The municipal water supply was thus attributed to the *wtr* input to services and households, whilst the *wtr* inputs into the rest of the economic sectors were re-classified as industrial water uses. The comparison of the water intensities of the two supply sectors revealed a greater value per m^3 for municipal water as a marker for higher treatment and distribution costs on this user segment.

This overall disaggregation of the GTAP database enabled the structuring of self-abstraction across the five broad categories of *irrigation*, *livestock*, *thermal power*, *industrial supply* and *municipal supply*. Water accounts were then added to these categories using the water use estimations from the WaterGAP/EXIOBASE database.

Chapter 6. Projecting irrigation water requirements across multiple socioeconomic development futures

6.1. Introduction

Meeting global crop demand relies to a large extent on enhancing soil moisture through irrigation, with 40% of global crop output currently obtained on irrigated land (Alexandratos & Bruinsma 2012). Hence, much of the past increases in food production came through the expansion of blue water use as a yield improvement measure. This practice has led to a steady growth in the use of irrigation with a doubling of global irrigable areas over the last five decades (Figure 6.1).

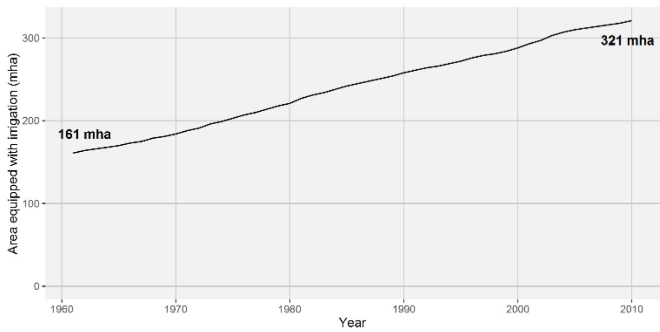

Figure 6.1 - Global area equipped for irrigation 1961-2010

Data source: FAOSTAT

Due to the dominant role of irrigation in overall withdrawals (70% at a global level), changes in crop demand could have significant implications for the overall human-induced pressure on freshwater resources. Demand for agricultural goods is expected to further expand in the next half century due to continued demographic and economic growth, raising questions about the role of irrigated crop production and on the sustainability of blue water withdrawals in agriculture. Expansions in water withdrawals for irrigation could thus be anticipated especially in high-growth developing regions that are also running out of suitable cropland. Therefore, understanding the dynamics of blue water uses within crop production systems given socioeconomic development and expected technological improvements is essential for assessing future demand-driven water deficits across the different world regions.

In this chapter, future water requirements are determined by taking into account multiple development storylines applied to the 2004-2050 timeframe. The characteristics of these alternative futures are derived from the recent Shared Socioeconomic Pathways (SSP) framework (van Vuuren et al. 2014). Future crop production and irrigation water demand are derived annually using the RESCU-Water model by considering changes both on the demand side (income and population) and supply side (factor availability, technological improvements). Given the advanced specification of crop production in the model, water requirements are determined "bottom-up" by accounting for input substitution possibilities and technological advancements detailed for every region, crop class and growing method (rainfed and irrigated). Withdrawal pressure is then expressed using the Irrigation Withdrawals to Availability (IWA) indicator, i.e. irrigation water requirements relative to total renewable water resources (TRWR).

As discussed in Chapter 3, future water demand in irrigation has mostly been assessed at a global-level in biophysical-type models. The structuring of irrigation water use in these studies and the water demand drivers used are presented in Table 3.1. Also, an overview of water use projections in relation to socioeconomic development limited to irrigation employing crop models is presented in Wada et al. (2016). The models used in these studies excel at having a detailed spatial representation of freshwater uses for crop production. Water requirements are linked to the expansion in food demand given income and population growth. However, these assessment frameworks do not embed any underlying microeconomic behaviour driving irrigation use or the crop demand-supply interactions, e.g. the price change impacts over crop demand, cropland conversion or inter-crop substitution.

Economic modelling focused on water as an input to production processes has dealt less with calculations of freshwater requirements by economic sectors. Among PE models, only IMPACT (Nelson et al. 2010) determines changes in beneficial water uses for crop production under socioeconomic development. However, the results already embed the constraints of any water deficits induced by exogenous water demand increases from other sectors. These values thus reflect the assumption of agriculture as lowest priority user and cannot be treated as measures of water resource pressure. Among studies using CGE models, only that in Roson & Damania (2016)[14] thoroughly embeds the evolution of water requirements in irrigation under different SSPs. The approach taken is "top-down" considering that irrigation water demand is calculated as a function of crop output and a constant sector-specific water intensity. Another study including elements of socioeconomic development is that in Fischer et al. (2007) where only one pathway is considered (SRES A2r). The water requirements determined are structured around four crop classes without any distinction between rainfed and irrigated production. The other global water CGE models treat the total use of irrigation water as exogenous and implicitly

[14] Referred to as the GTAP-RD model in Chapter 3

cannot account for changes in irrigation water requirements as a function of changes in crop demand[15].

Concerning the physical freshwater supply constraints, it is difficult to assess how much freshwater can be physically abstracted from the environment at a global scale and even more so to determine how much can be employed for irrigation. On the one hand, river basins can be overexploited through a persistent reliance on excessive groundwater pumping. There is evidence that currently there are extended areas where water tables are decreasing (Smakhtin et al. 2004; Döll et al. 2014; Long et al. 2015; Wada et al. 2010) indicating withdrawals above TRWR levels. Nevertheless, considering the large volumes of water stored in aquifers (see Chapter 2, Table 2.1) no upper withdrawal limit in the coming decades can be taken for granted unless exploring scenarios of sustainable water use i.e. withdrawals not exceeding the river basin recharge rate minus other provisions for the environment. On the other hand, without considering the evolution of other freshwater demand drivers (industry, services and households) by systematically using the same assumptions about socioeconomic development, it is not possible to ascertain the water volumes that are available to crop production even when a total withdrawal limit can be considered. Hence the assessment in this chapter does not take into account any physical constraints for irrigation freshwater supply associated with decreases in water tables or to the depletion of river flows. Therefore, the IWA indicator used here should be regarded as an indicator of pressure over the resource base and not as a reflection of actual irrigation withdrawals in the future.

The results in this chapter also serve as a starting point for the construction of a water demand baseline in a world where water use constraints and climate change incidence are not considered. The relationship between climate change and water use patterns in irrigation is explored in Chapter 7. The irrigation water requirements obtained here are complemented in Chapter 8 with projections of non-crop water demand and are used to determine the scale of future water deficits across world regions.

The chapter is structured as follows. Section 6.2 presents the RESCU-Water model configuration for this application. Section 6.3 gives a brief overview of the alternative futures considered. Section 6.4 presents the relevant model results – changes in crop output and irrigation requirements, irrigation pressure evolution using the IWA indicator, and changes in virtual water

[15] This approach has flaws considering that fixing the supply of irrigation can still lead to changes in water uses due to the possibility of switching irrigation and land between low-water intensity to high-water intensity crops. This was also discussed in Chapter 3 (Section 3.3.2.9).

flows associated with international trade. A discussion of results and the consideration of limitations of this study are done in Section 6.5. Section 6.6 concludes.

6.2. Methods

6.2.1. CGE modelling for projecting irrigation use

The advantage of using a CGE framework to determine changes in freshwater withdrawals comes from the framework's capability to represent factor allocation across sectors. The effects of economic growth and those of changes in population can thus be captured on the supply side by tracking the accumulation of capital stock and the evolution of labour supply and labour productivity. On the demand side, socioeconomic development translates into changes in final and intermediate demand of commodities given the spending behaviour of the different agents (households, government and investment).

Furthermore, as an input to production, irrigation needs to be represented in relation to the other factors regarding substitution possibilities and feedback effects as a consequence of technological change. With an economy-wide view, CGE models can capture the relationship between factor productivity gains and the sectoral demand for that input. Specifically, with respect to irrigation, yield growth leads to a reduction in land requirements per unit of output and implicitly reduces the land market prices through an overall reduction in arable land demand. These exogenous yield improvements then lower the total cost of production resulting in a rebound growth of demand for crops and subsequently of irrigation.

The use of a global CGE framework is also relevant for tracing the impact of international trade on freshwater withdrawals. With crops being some of the most intensely traded commodities, a multi-regional approach includes the effects of crop trade on irrigation withdrawal pressure. CGE models can, therefore, be used to map the flows of 'virtual water' embedded in international trade. The virtual water concept was established in Allan (1997) and is now used to determine the water footprint of world regions (Hoekstra & Mekonnen 2012) and that of international trade (Roson & Sartori 2010; Liu et al. 2013; Berrittella et al. 2005; Hoekstra & Hung 2005). As this chapter is focused on irrigation, the virtual water results refer to the embodied blue water content associated with crop trade. The inclusion of 'virtual water' trade enables the analysis of whether water exports to regions that are land- or water-constrained are likely to replace some of the domestic production of irrigation-intensive goods with imports and thus avoid further increases in pressure over their endowments.

6.2.2. RESCU-Water model configuration

The calculation of irrigation water requirements is conducted by using the assumption of unconstrained water supply. Therefore, the RESCU-Water configuration includes some simplifications to the model description in Chapter 4. As water scarcity is not considered in this calculation, water as a factor with a market price is not included in the model production functions. The resulting production tree for irrigated crops is presented in Figure 6.2.

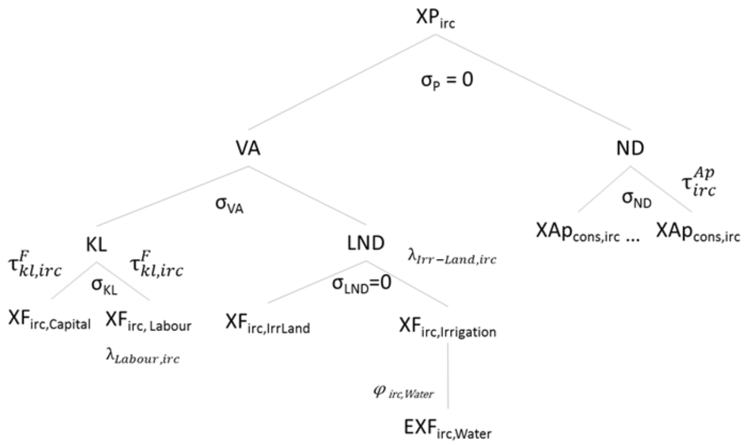

Figure 6.2 - Equivalent RESCU-Water irrigated crop production functions

The *LND* land-related inputs are composed only of irrigated land and irrigation. Water demand by crop class is considered as a model variable EXF^{irc}_{Water}, which does not influence demand decisions of non-water inputs. The demand is calculated for each irrigated crop *irc* through a model identity equation in which irrigation demand $XF^{irc}_{Irrigation}$ is multiplied with the crop-specific water intensity $\phi_{irc,Water}$ (6.1).

$$EXF^{irc}_{Water} = \phi_{irc,Water} * \quad XF^{irc}_{Irrigation} \tag{6.1}$$

The water intensities can vary significantly both across regions and across crop classes (Figure 6.3). Therefore considering that *Irrigation* is a fully mobile factor, the re-allocation of its use from one crop production to another would lead to different irrigation water requirements depending on the water intensity differences between crop types.

Expected technological changes are embedded in the model through yield improvements with data obtained from the IMPACT model (Nelson et al. 2010). The implemented yields differentiate crop performance changes by region, crop class and growing method (rainfed and irrigated). These changes are applied as exogenous alterations to land-input factor productivities - the $\lambda_{Irr\text{-}Land,irc}$ and $\lambda_{RfLand,rfc}$ parameters for irrigated and rainfed crop respectively (see Figure 4.4 in Chapter 4 for the rainfed crop production).

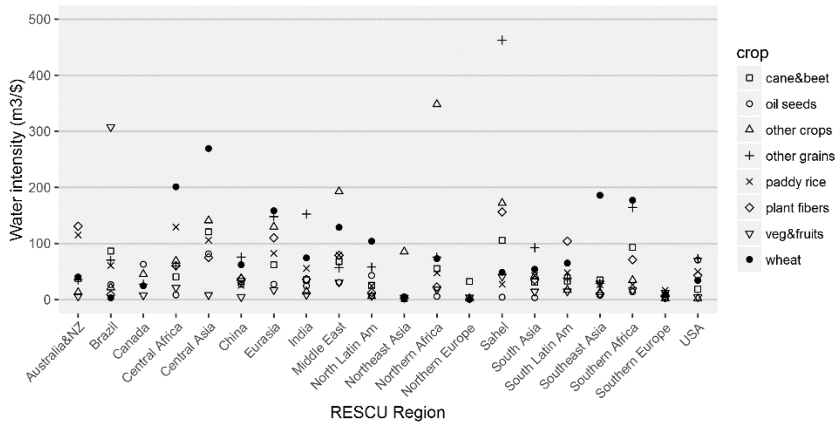

Figure 6.3 - Blue water intensities of irrigation water value added - by crop and by region

Source: calculated from the RESCU-Water base year data

6.2.3. Factor supply changes

In model simulations, capital and labour supply levels are updated annually to reflect changes induced by socioeconomic development. Capital stock follows investment and depreciation whilst labour is adjusted based on the evolution of the 15-65 years age groups within each region. As the base year comprises investment levels in developing regions that are high and unlikely for the long run, investment shares are adjusted by following the dynamics determined by the macro-econometric MaGE model (Fouré et al. 2013) for each SSP considered. Also, a labour productivity factor is endogenised in order to meet the annual GDP growth targets in the model simulations.

Land supply and the conversion from rainfed to irrigated cropland are important determinants of irrigation water requirements outcomes. As described in Chapter 4 section 4.4.2.6, the supply of arable land is specified through a two-stage mechanism. Total cropland supply is introduced as a logistic function following land rent changes. The availability of arable land thus reacts to market prices – when the price of land use *PALand* exceeds the regional price index *PINDEX*, additional supply is brought in to counter price inflation. In a second stage, cropland is split into rainfed and irrigated land using a CET function. Given that there are no estimates of the transformation elasticities for the two land types at national or regional levels, the CET function is calibrated by assuming an elasticity of 2. The choice of this value is made to indicate a moderate ease of conversion from one type of land to another[16]. Nevertheless, the impact of

[16] Lower than the value of 10 used in GTAP-BIO-W (Taheripour et al. 2013b)

altering this assumed value does not change the model results significantly (see sensitivity analysis in the Discussion section 6.5.3).

Considering the Leontief (no substitution) nesting of irrigable land (*IrrLand*) and irrigation, the supply of *Irrigation* is calibrated to follow the changes in available arable land such that this would not impose a significant constraint on the expansion or contraction of the *Irrigation-Land* bundle demand[17]. This calibration is done by setting *IrrMax* to a value higher than *LandMax* for every region[18].

6.2.4. Irrigation Withdrawals to Availability indicator

The inclusion of irrigation as a distinct input to production allows for an accounting of irrigation water requirements that tracks the changes in crop output and substitution effects between factors of production. Total regional requirements are calculated using the summation of irrigation water uses EXF_{Water}^{irc} for each irrigated crop type *irc*.

$$Irrigation\ water\ requirements_r = \frac{\sum_{irc} EXF_{Water}^{irc,r}}{\eta_r} \tag{6.2}$$

Here η_r represents the regional irrigation efficiency which includes field application and conveyance losses. These were calculated for each RESCU region by following the procedure and irrigation country data from Rohwer et al. (2007) as described in Chapter 5 section 5.3.1.1. The overall values obtained range from 38% to 86% depending on the conveyance method and the technological mix of irrigation within each region.

To measure the evolution of pressure coming from irrigated crop production the Irrigation Withdrawals to Availability (IWA) indicator is introduced. IWA is a measure of total water requirements relative to Total Renewable Water Resources (TRWR) in each RESCU region:

$$IWA_r = \frac{Irrigation\ water\ requirements_r}{TRWR_r} \tag{6.3}$$

In line with the Withdrawals to Availability (WTA) indicator introduced in Alcamo et al. (2003) and the Water Stress Index (WSI) from Fischer et al. (2007), an IWA threshold of IWA ≥ 0.2 is set for medium pressure and IWA ≥ 0.4 for severe pressure of irrigation withdrawals exerted over available renewable resources.

[17] This is observed in model simulations without yield changes embedded where price differentials of $IrrLand$ and $IrrWater$ are negligible

[18] A value of 5 was used implying that the irrigation can expand up to five times the base year level. This value is in accordance with the cropland expansion possibilities – see Table 4.4 in Chapter 4.

6.2.5. Expansion mechanisms of irrigation water use

Starting from the two main drivers – socioeconomic development and technological change - modifications in total water requirements can occur through multiple channels (Figure 6.4). A distinction is made between the 'scale' effect determined by changes in the output of crops and a 'substitution' effect determined by factor substitution within crop production functions, and between crop types and varieties.

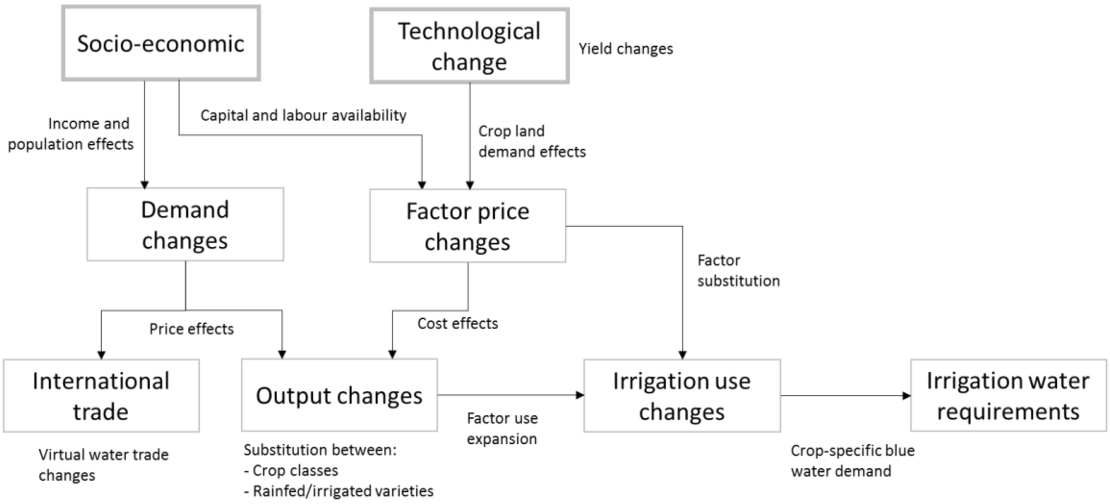

Figure 6.4 - Mechanisms of withdrawal changes

For the 'scale' effect, income and population growth lead to higher overall demand for crops given the household LES utility function and the underlying commodity income elasticities. These changes in demand are met either by domestic supply or through international trade. Given the CGE market clearing and zero economic profit conditions, changes in labour and capital stock availability induced by socioeconomic evolution also have a scale impact on domestic supply through changes in costs of domestic production.

Relative price changes of production factors lead to a 'substitution' effect between inputs as suggested by the elasticities in the nested production functions from Figure 6.2. At the same time, the crop-specific changes to land productivity have an impact on crop production costs. Hence, a substitution between crop classes and also between the irrigated and rainfed varieties within the same crop class can occur based on cost advantages of one commodity over another. These changes in the crop production mix determine a re-allocation of irrigation across crop types and ultimately lead to alterations to water requirements at a regional level.

6.3. Alternative futures scenarios

The withdrawal and IWA values are determined for three SSP scenarios (SSP1, SSP2 and SSP5). A snapshot of the selected pathways is presented in Table 6.1 with the regional growth rates in GDP and population in Figure 6.5. It should be noted that SSP1 is labelled as the 'sustainability' future from a greenhouse gas emissions perspective and not from that of resource use in general. Also, the growth patterns assumed by these storylines are linked to carbon concentration outcomes but do not incorporate the possible feedback effect of climate change on socioeconomic development.

Table 6.1 – Description of selected SSPs

SSP scenario	**Details**
SSP1 – Sustainability	Rapid development of low-income countries, reduction of inequality between economies; globalised economy; reduced dependency on fossil fuels and reduced resource intensity; adoption of clean energy technologies awareness of environmental degradation Model implications: **high** GDP growth in developing countries and **medium** in developed countries, **medium** population growth
SSP2 – Middle of the Road	Same trends as in previous decades; disproportionate development of low-income economies; global income per capita increases at a medium pace; reduction of energy intensities; some decrease of dependency on fossil fuels Model implications: **medium** GDP growth, **high** population growth
SSP5 – Conventional Development	Orientation towards economic growth; energy systems dependent on fossil fuels; highly-engineered infrastructure Model implications: **high** GDP growth, **medium** population growth

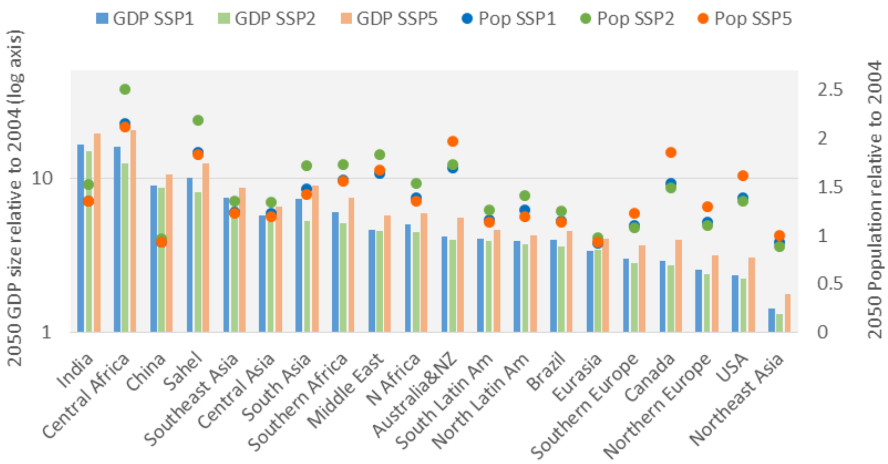

Figure 6.5 - Regional GDP and population in 2050 relative to 2004 levels

Data source: IIASA SSP database

In the RESCU-Water model, the SSPs are implemented through GDP growth rates and population changes. GDP growth leads to an overall increase in demand for goods as total income rises whilst the demographic evolution has two distinct consequences. On the one hand, the subsistence consumption component of the LES utility function expands due to population growth. On the other hand, the supply of labour follows the changes in total active population stemming from a flattening of population growth by 2050. Downscaled socioeconomic data are taken from the IIASA SSP database[19]. For each SSP, the derived growth rates of the relevant variables (real GDP, subsistence consumption, active population) are applied over the 2004-2050 horizon through annual simulation time steps.

6.4. Results

6.4.1. Crop output

Crop output expands across all regions and virtually across all crop classes. Globally, crop production is projected to grow by 87.6% (SSP1), 83.2% (SSP2) and 101.1% (SSP5) by 2050 from 2004 values. At a regional level, total output growth ranges from 12% (Northeast Asia) to 294% (Sahel) in SSP2 (Table 6.2). A higher output expansion takes place in regions with more pronounced socioeconomic development (Africa, Middle East, South Asia) and in those that are important crop exporters (Australia, USA). Irrigated production grows more than that on rainfed land across all regions mainly due to larger inherent yield improvements. Overall, irrigated agriculture increases its importance in world crop output; however, rainfed production continues to represent the larger share at a global level – the share of irrigated crop production grows from 36.0% in 2004 to 39.6% in 2050 for SSP2 and similar weights for SSP1 and SSP5.

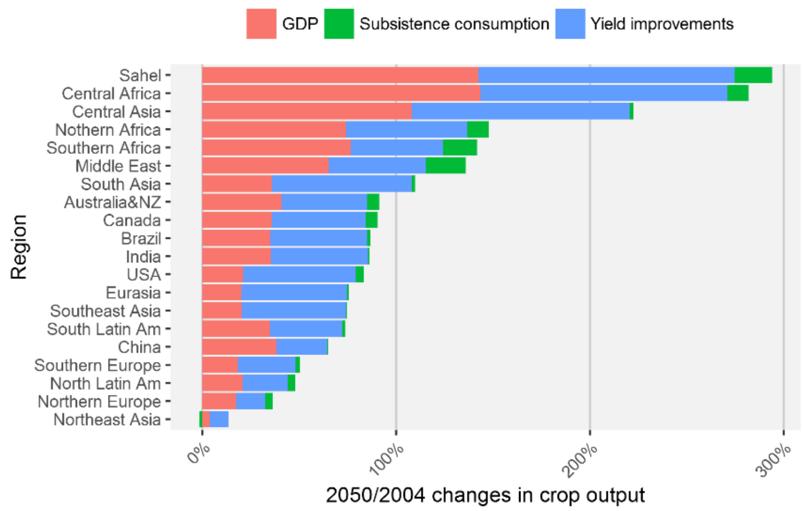

Figure 6.6 - Decomposition of crop output growth in 2050 relative to 2004 levels - SSP2

[19] https://tntcat.iiasa.ac.at/SspDb/

GDP growth and yield improvements have the highest impact on crop production in all regions (Figure 6.6). Income growth leads to a crop demand expansion, whilst yield improvements further boost crop output through a reduction in costs of production. Increases in subsistence consumption driven by population growth have a limited effect, however, this is still visible in many regions. This low contribution of population growth is due to a significant expansion of disposable income which reduces the weight of subsistence spending in the overall household budget. Meeting subsistence consumption becomes thus less of a constraint in the budget allocation across consumer goods.

Table 6.2 – SSP2 crop output growth in 2050 relative to 2004 levels

	Total	irrigated	rainfed	wheat	rice	other grains	veg& fruits	plant fibres	cane& beet	oil seeds	other crops
Australia&NZ	91.4%	104.4%	80.1%	81.4%	120.6%	75.1%	122.7%	111.4%	39.7%	21.1%	48.4%
Brazil	86.6%	135.6%	78.4%	131.0%	63.3%	50.8%	69.8%	120.8%	88.0%	129.5%	65.5%
Sahel	293.9	274.6%	297.0%	54.6%	187.1%	346.8%	333.8%	175.5%	186.9%	248.1%	120.4%
Central Africa	281.9	586.3%	265.4%	670.4%	283.8%	327.9%	324.8%	239.4%	232.9%	238.0%	124.5%
Central Asia	222.5	237.6%	191.1%	239.6%	301.8%	324.2%	264.6%	129.4%	259.7%	110.9%	(25.0)%
China	64.9%	108.9%	39.8%	15.7%	18.8%	106.4%	72.7%	197.4%	138.2%	33.8%	35.7%
Eurasia	75.3%	95.2%	73.1%	73.7%	94.0%	69.8%	72.4%	160.4%	99.6%	91.5%	99.3%
India	86.0%	108.9%	71.6%	222.7%	70.3%	303.1%	56.5%	114.3%	19.6%	89.3%	42.6%
Middle East	135.9	159.6%	100.5%	129.4%	107.3%	153.2%	129.0%	206.6%	145.3%	204.0%	106.4%
Northern Africa	147.7	132.3%	178.5%	177.6%	104.3%	95.6%	143.8%	213.5%	149.5%	120.0%	154.7%
NE Asia	12.0%	8.4%	14.7%	38.1%	2.4%	116.5%	16.2%	73.9%	1.2%	75.3%	14.2%
Northern Europe	36.2%	49.6%	34.3%	34.4%	158.6%	41.1%	18.8%	43.3%	57.9%	34.7%	43.9%
Northern Lat Am	47.9%	60.5%	39.3%	23.4%	46.3%	61.2%	49.8%	126.5%	93.2%	42.3%	19.9%
Canada	90.3%	132.0%	84.8%	97.5%	54.3%	76.5%	184.1%	57.0%	61.7%	59.0%	46.5%
Southern Africa	141.8	162.2%	118.6%	260.2%	89.8%	186.4%	133.1%	143.2%	131.7%	87.4%	113.0%
South Asia	109.8	98.7%	172.0%	30.8%	57.8%	156.0%	274.0%	73.3%	104.6%	158.6%	16.3%
SE Asia	74.4%	110.2%	61.2%	476.1%	24.9%	53.3%	139.6%	193.9%	37.8%	80.1%	33.5%
Southern Europe	50.5%	73.9%	38.0%	56.8%	67.3%	43.6%	27.4%	40.8%	86.5%	80.4%	58.8%
Southern Lat Am	73.9%	93.5%	66.9%	81.4%	53.7%	87.5%	49.6%	162.3%	91.1%	88.6%	25.3%
USA	83.4%	91.3%	74.3%	121.9%	133.1%	50.2%	82.0%	127.7%	43.0%	121.4%	73.1%
World	**83.2%**	**101.3%**	**73.0%**	**97.7%**	**38.0%**	**109.5%**	**90.9%**	**149.2%**	**79.0%**	**95.8%**	**52.5%**

6.4.2. Irrigation water requirements

Global irrigation water requirements in 2050 are projected to reach 2 605 km^3 (SSP1), 2 583 km^3 (SSP2) and 2 645 km^3 (SSP5) representing a 9.4%, 8.5% and 11.1% increase for SSP1, SSP2 and SSP5 respectively from 2004 levels. In most regions water withdrawals expand with changes in Central Africa, India, Sahel and Central Asia (Figure 6.7). In these regions, higher growth SSPs (SSP1 and SSP5) exacerbate the increases in water requirements. In cases where a decrease occurs, the results are more mixed – higher global socioeconomic development further alleviates pressure from withdrawals in one group (Canada and China) but partially offsets this reduction for another group of regions (Southeast Asia, Eurasia and South Asia). The differences between these two groups are dictated by the relative sizes of the 'scale' and 'substitution' effects as outlined in Section 6.2.5.

Table 6.3 – IWA in 2004 and 2050 by SSP

Region	2004	2050		
		SSP1	SSP2	SSP5
S Asia →	103.89%	103.56%	102.78%	103.96%
N Africa ↗	76.80%	89.70%	88.43%	91.75%
Middle East ↗	58.17%	62.17%	62.38%	64.93%
India ↗	31.61%	42.32%	41.68%	43.49%
C Asia ↗	16.41%	19.59%	19.75%	20.31%
China ↘	12.86%	10.38%	10.45%	10.07%
USA ↗	7.58%	8.24%	8.20%	8.16%
S Europe ↗	7.13%	7.18%	7.15%	7.32%
S Africa ↗	5.55%	6.12%	6.06%	6.26%
SE Asia ↘	2.91%	2.87%	2.84%	2.90%
Australia&NZ ↗	1.78%	1.91%	1.89%	1.96%
NE Asia →	1.84%	1.84%	1.84%	1.84%
N Latin Am ↗	1.37%	1.43%	1.42%	1.43%
S Latin Am ↗	1.08%	1.23%	1.23%	1.26%
Sahel ↗	0.78%	1.09%	1.00%	1.18%
Central Africa ↗	0.61%	1.01%	0.92%	1.11%
Eurasia ↘	0.43%	0.42%	0.42%	0.42%
Brazil ↗	0.13%	0.14%	0.14%	0.14%
N Europe ↘	0.07%	0.07%	0.07%	0.07%
Canada ↘	0.07%	0.06%	0.07%	0.06%

The obtained increases in withdrawals have a significant impact on already water-challenged regions. Irrigation pressure continues to grow in regions with an IWA over 20% in the base year. The metric reaches values of 88-92% in Northern Africa, and 64-68% in the Middle East (Table 6.3). India enters the high-pressure domain with a projected IWA of 42-43% in 2050. Furthermore, Central Asia faces significant increases in the IWA values across the SSP scenarios and hence in SSP5 goes beyond the 20% stress threshold for medium pressure. South Asia is the only region in which irrigation water requirements are comparable to 2004 levels. However, the IWA of over 100% suggests continued river basin over-exploitation across the region. This general tendency towards an increase in water requirements, if translated into actual withdrawals, will further deteriorate the irrigation water stress map across a wide geographical area spanning from Northern Africa to Central Asia (see Figure A1 in Annex A).

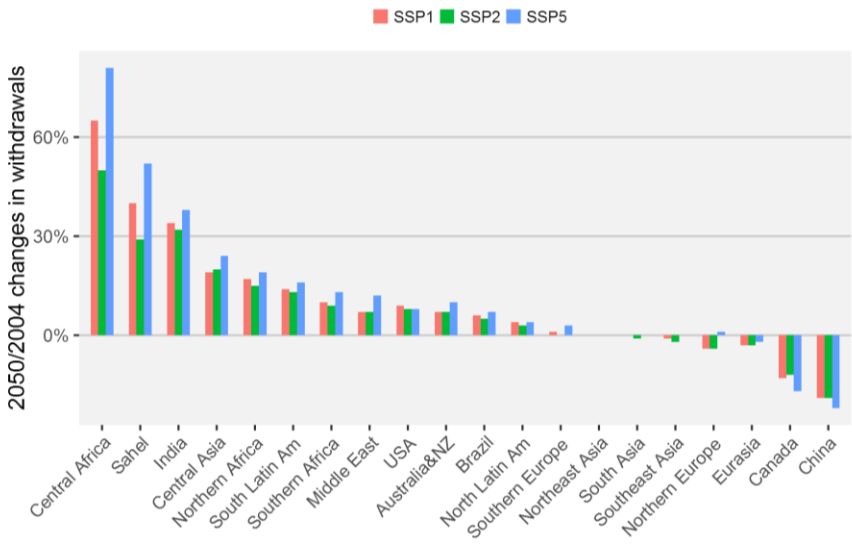

Figure 6.7 - Regional irrigation withdrawal changes in 2050 relative to 2004 levels

6.4.3. Irrigation supply and allocation

If the 'scale' effect of socioeconomic development over irrigation withdrawals is highlighted by the general crop output expansion, the 'substitution' effect is determined by changes in factor allocation across time given relative yield improvements and factor availability modifications. This re-distribution of means of production leads to alterations in the way irrigation is used across the eight crop classes and implicitly determines changes in water requirements considering the differences in blue water intensities between crop classes.

For SSP2, irrigation supply increases 9.0% globally by 2050 (Table 6.4) with a variation across regions ranging from -1.0% (Northeast Asia) to 104.2% (Central Africa). In addition to this overall growth, there is a re-allocation of irrigation uses between crops. *Wheat* production in India nearly doubles its use of irrigation water determining the single most important increase in withdrawals. The increase is only slightly counter-balanced by the reductions in irrigation water use of other crops (*plant fibers*, *oil seeds* and *other crops*). For China, despite an overall increase of 13.5% in irrigation supply, total withdrawals decrease. Irrigation here is reallocated from cereals (*wheat*, *rice* and *other grains*) to less water-intensive crops for this region (*veg&fruits*, *cane&beet*) lowering the withdrawal impact of the overall use of irrigation. Similarly, in South Asia, the considerable reduction in water use for *wheat* is accompanied by a notable increase in

Table 6.4 - Changes in irrigation uses and in irrigation water requirements in 2050 relative to 2004 levels - SSP2

	Changes in irrigation use (%)									**Changes in irrigation water withdrawals (km^3)**								
	wheat	rice	other grains	veg&fruits	plant fibres	cane&beet	oil seeds	other crops	**overall**	wheat	rice	other grains	veg&fruits	plant fibres	cane&beet	oil seeds	other crops	**overall**
Australia&NZ	2.1%	79.2%	19.5%	(2.2)%	(24.1)%	(2.4)%	10.4%	43.5%	**6.3%**	0.01	1.42	0.14	(0.05)	(1.08)	(0.08)	0.00	0.59	0.95
Brazil	13.5%	7.2%	(13.1)%	14.4%	(7.8%	(14.2)%	70.6%	2.9%	**4.2%**	0.00	0.33	(0.02)	0.36	(0.01)	(0.26	0.08	0.04	0.53
Sahel	(26.0)%	(7.0%	(32.0)%	62.3%	(59.6)%	63.3%	100.6%	184.0%	**37.9%**	(0.06)	(0.33)	(0.09)	0.75	(0.06)	0.52	0.00	1.57	2.31
Central Africa	(98.9)%	23.7%	(33.6)%	304.6%	(73.1)%	(84.8)%	(91.2)%	99.2%	**104.2%**	(0.09)	1.77	(0.29)	5.78	(0.50)	(1.55)	(0.12)	3.02	8.01
Central Asia	220.2%	29.2%	147.9%	57.5%	(18.8)%	70.8%	0.7%	(46.7)%	**28.1%**	10.55	1.31	9.26	4.43	(7.90)	0.32	0.00	(3.20)	14.79
China	(37.5)%	(22.5)%	(29.0)%	108.8%	(49.9)%	73.2%	6.1%	(89.9)%	**13.5%**	(23.36)	(47.05)	(15.58)	20.63	(3.83)	2.39	0.80	(3.82)	(69.82)
Eurasia	(17.3)%	(9.7%	(20.3)%	10.0%	19.0%	(20.5)%	50.5%	35.1%	**1.9%**	(1.06)	(0.14)	(0.93)	0.29	0.19	(0.16)	0.11	1.06	(0.62)
India	93.9%	15.8%	(67.1)%	20.4%	(36.1)%	(4.4%	(69.7)%	29.5%	**21.5%**	178.70	32.84	(10.17)	6.63	(10.32)	(3.49	(11.75)	8.49	190.94
Middle East	(13.9)%	(5.7)%	11.7%	17.1%	10.2%	(2.1)%	33.8%	9.7%	**12.2%**	(5.52)	(1.07)	2.17	14.65	2.05	(0.22)	1.02	4.25	17.33
Northern Africa	(28.3)%	34.0%	(43.2)%	9.8%	44.0%	35.9%	26.6%	69.5%	**10.6%**	(6.53)	5.44	(10.68)	4.58	3.39	4.21	0.32	24.43	25.17
NE Asia	4.7%	(1.2)%	(24.1)%	(5.0)%	27.1%	(8.4)%	95.6%	8.9%	**(1.0)%**	0.00	(0.10)	(0.04)	(0.01)	0.00	0.00	0.13	0.02	0.00
Norhtern Europe	(21.7)%	85.9%	(20.7)%	(17.5)%	19.7%	18.5%	(30.5)%	9.4%	**3.8%**	0.00	0.00	0.00	(0.09)	0.00	0.04	0.00	0.02	(0.04)
North Latin Am	27.2%	(7.3)%	(22.6)%	4.2%	23.5%	6.0%	107.5%	0.7%	**3.3%**	2.92	(0.81)	(2.99)	1.22	0.65	1.10	1.04	0.06	3.18
Canada	(28.6)%	24.0%	(28.1)%	48.1%	20.2%	(1.4)%	1.5%	(23.1)%	**4.3%**	(0.17)	0.00	(0.11)	0.12	0.00	0.00	0.01	(0.11)	(0.27)
Southern Africa	(5.9)%	27.5%	73.4%	20.8%	31.7%	(24.6)%	(61.0)%	15.3%	**13.1%**	(0.10)	0.03	0.57	0.68	0.27	(0.59)	(0.12)	0.31	1.04
South Asia	(27.9)%	11.6%	44.4%	147.1%	(3.0)%	6.7%	(10.7)%	(14.6)%	**8.9%**	(33.07)	7.01	5.81	20.63	(1.25)	1.70	(0.18)	(3.86)	(3.21)
SE Asia	80.0%	(28.2%	(75.3)%	289.8%	(29.6)%	(16.4)%	(19.1)%	144.3%	**9.2%**	8.48	(44.43)	(1.37)	28.45	(0.04)	(1.92)	(0.18)	6.58	(4.44)
Southern Europe	(12.1)%	12.9%	(9.6)%	(1.4%	21.6%	6.0%	27.7%	(6.5)%	**0.4%**	(0.23)	0.50	(1.21)	(0.37)	1.15	0.13	0.84	(0.64)	0.17
South Latin Am	37.1%	3.9%	59.6%	(2.8)%	32.1%	37.1%	258.0%	(18.9)%	**4.5%**	0.33	0.12	0.88	(0.27	0.12	0.56	1.46	(0.50)	2.69
USA	22.7%	34.7%	(13.3)%	7.7%	0.9%	0.7%	46.7%	(8.0)%	**2.3%**	2.73	6.16	(6.18)	2.07	0.21	0.02	8.68	(0.70)	12.99
World	**22%**	**(9)%**	**(13)%**	**30%**	**1%**	**1%**	**7%**	**1%**	**9%**	133.54	(36.99)	(30.83)	110.47	(16.95)	2.73	2.15	37.61	201.72

irrigation employment for *veg&fruits* which are more water-productive. Globally, changes in irrigation use patterns lead to significant withdrawal increases for *wheat* (coming mainly from India and Central Asia), *veg&fruits* (China, India, South Asia, Middle East, Southeast Asia), and decreases for *rice* (China, Southeast Asia) and *plant fibers* (India, Central Asia).

6.4.4. Virtual water flows through international trade

Global flows of virtual blue water expand from 255 km^3 in 2004 to 288 km^3 (SSP1), 282 km^3 (SSP2) and 296 km^3 (SSP5) in 2050. Some regions make considerable savings on their irrigation withdrawals through international trade (Figure 6.8a) either by reducing the export of water-intensive crops (Central Asia, Middle East) or by increasing imports (India, China, Central Africa Northern Africa, N Latin America). On the other side of the spectrum, more withdrawals are determined by the export of more crops (South Asia, Southeast Asia, USA) and through fewer imports complemented by increases in domestic crop production (Northeast Asia, Northern Europe, Southern Europe) - Figure 6.8b.

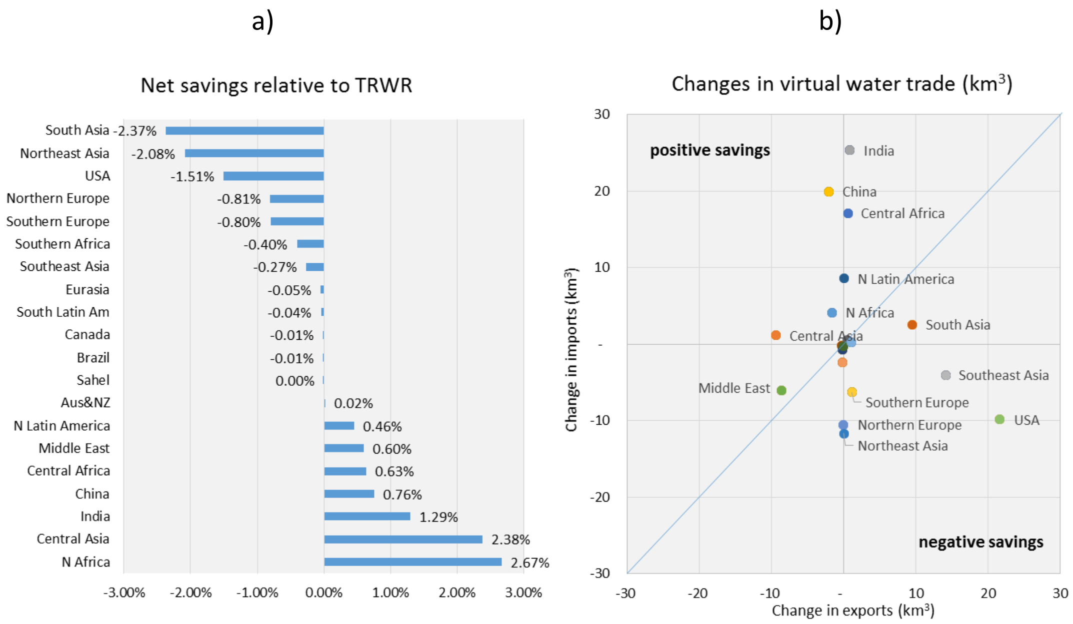

Figure 6.8 – Changes in virtual water trade in 2050 relative to 2004 levels – SSP2

The analysis of virtual water flows shows that water-stressed regions are exporting considerable volumes of freshwater and many continue to do so in the future (Figure 6.9). In South Asia, the exports of crops (notably *veg&fruits* to India) become an important weight in withdrawals by 2050 (6% of TRWR). Therefore, in this region, the reduction in withdrawals coming from the re-allocation of irrigation across crops on the supply side is offset by the growth in net virtual water exports. At the same time, although important exporters initially, the Middle East and Northern Africa see a reduction in exports of virtual water across all destination regions.

It should be noted that at a regional level these changes do not necessarily imply changes in the same direction of total physical flows of crops. With different water intensities depending on the crop class and the production region, an overall change in virtual water exports may be coming from changes in the structure of exported crops. Although volumes of trade in crops may be of interest from a food security perspective, these fall outside the scope of this chapter.

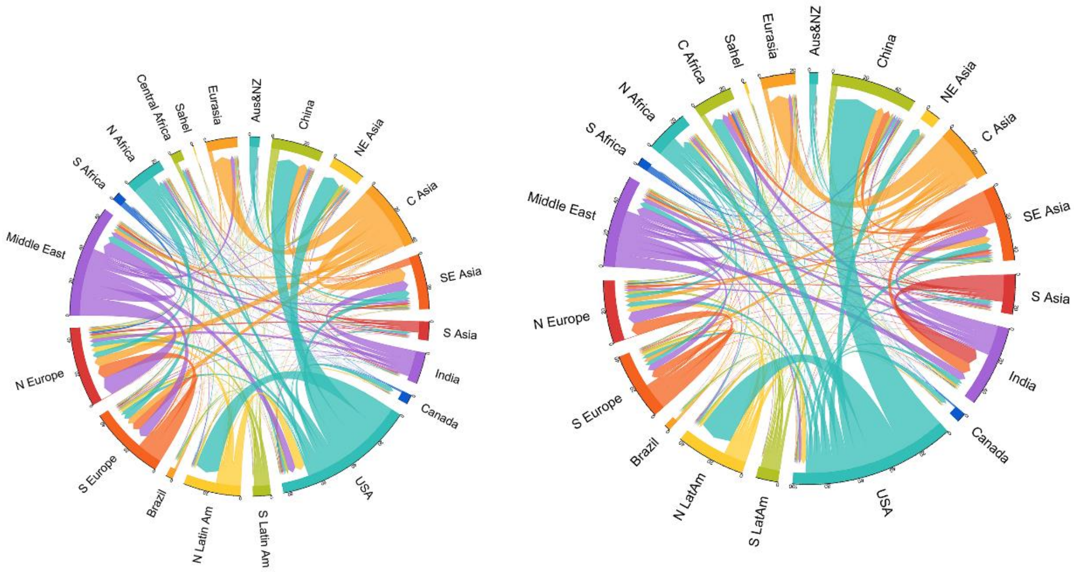

Figure 6.9 - Virtual water flows in 2004 and 2050 – SSP2

Virtual water flows represent 255 km^3 in 2004 and 288 km^3 in 2050. The arrows show the exporter to importer direction of flows. Flows within a region are determined by trade between countries belonging to the same RESCU-Water region.

6.5. Discussion

6.5.1. Importance of socioeconomic drivers and yield changes

Socioeconomic development has a non-negligible impact on irrigation water withdrawals. The results are more pronounced in scenarios with higher economic growth for developing economies (SSP1 and SSP5), indicating the importance of income for the pressure over freshwater resources in these regions. Furthermore, whilst growth in irrigation use can be explained to a large extent by increases in domestic demand for crops, changes in crop trade can also have a visible impact on irrigation water requirements. Hence, some regions face strong virtual water export increases due to growth in demand elsewhere (e.g. *veg&fruits* from Southeast Asia and South Asia to India).

From a technological change perspective, yield improvements are equally as important for future irrigation water requirements (Figure 6.10). In the model, increases in yields lead to a reduction in land and irrigation demand in most regions (e.g. Central Africa, Northern Africa, Middle East). However, in some cases, the resulting cost reductions bring about a rebound effect by further stimulating demand for water-intensive crops and implicitly that for irrigation water (India, Sahel, South Asia). In China, the relative changes in yields between rainfed and irrigated varieties are the main factor leading to the considerable reduction in irrigation withdrawals.

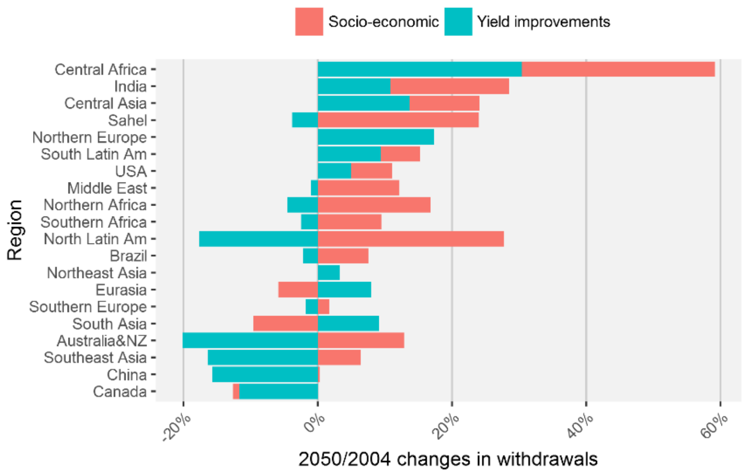

Figure 6.10 - Contribution of socioeconomic drivers and yields to overall water requirements changes in 2050 relative to 2004 levels – SSP2

6.5.2. Comparison to other recent assessments

The obtained results of an 8.5-11.0% increase in global freshwater withdrawals are situated within the range obtained from other studies. The expert judgement in Bruinsma (2009) which determines a 70% increase in agricultural output globally, leads to an 11% increase in withdrawals. The outlook in Alexandratos & Bruinsma (2012) gives a 6% increase for withdrawals in 2050 from 2005/2007 levels. The higher absolute values obtained (2 926 km^3 in 2050) are also a function of the base year withdrawal values[20]. At the same time, the lower increases in withdrawals may be explained by the use of a conservative scenario for socioeconomic development. As an underlying metric to withdrawals, Nelson et al. (2010 p.73) through the IMPACT model obtain increases in beneficial water consumption over the 2010-2050 horizon of 17.2-28.1% and 7.9-18.0% for a set of SRES pathways with and without irrigation efficiency gains respectively. Further on, the IMPACT irrigation withdrawal results for SSP2 and no climate

[20] 2 761 km^3 in 2005 also comprising categories which are not considered in this analysis (flooding of paddy rice fields and irrigation of pasture land), compared to 2 382km^3 in RESCU-Water for 2004.

change incidence show a 15.9% increase in 2050 from 2005[21]. In World Bank (2016), the irrigation withdrawals are considerably higher with a 65% increase between 2005 and 2050 for SSP2, reaching about 3800km^3. This significant expansion could be due to the “top-down” specification of crop production systems, as discussed in Chapter 3 section 3.3.2.8, through which the ‘substitution’ effect is not accounted for properly. Fischer et al. (2007) obtain a 15.4% increase in requirements between 2004 and 2050[22] for SRES A2r without climate change.

At a regional level, these assessments generally present an increase in irrigation withdrawals across developing economies. Therefore, the RESCU-Water results show similar trends for Northern Africa, Central Africa, Middle East, India and Latin America but opposing results for China and South Asia. The reduction in irrigation water for China is also obtained by IMPACT for the SSP2 scenario with comparable irrigation allocation across crops. For industrialised regions, expert judgement leads to a significant decrease in withdrawals. In contrast, IMPACT blue water uses increase in regions with extensive irrigation, e.g. the USA, similarly to the results in this chapter. It can thus be observed that assessments which are reliant on expert judgment (Alexandratos & Bruinsma 2012) tend to have a more uniform effect of socioeconomic development over withdrawals, whereas modelled projections may lead to opposing effects among regions with similar prospects of development.

Compared to the IMPACT results for SSP2, the most important discrepancies observed for water-stressed regions refer to the allocation of blue water across crops in India and withdrawal trends in South Asia. For India, we obtain an increase in withdrawals for *wheat* complemented by decreases for other crops, whereas IMPACT obtains a more balanced increase across all crop classes. In South Asia, a marked decrease in *wheat* blue water use is also obtained, however, in IMPACT the growth for all other crops overcompensates for this which is leading to an overall expansion in demand for irrigation water.

In terms of crop production expansion, the results are similar to those obtained in other global CGE models. The AgMIP model comparison in Valin et al. (2014) led to increases in crop demand in the range of 50-97% under SSP2 between 2005 and 2050. Therefore, the results obtained here (83.2% increase) are on the upper end but still well within the interval of values of the model inter-comparison project – see Annex A Table A2 for a further comparison with AgMIP models.

[21] Obtained from the IMPACT model portal - http://impact-model.ifpri.org/#scenario/SSP2_NoCCwater/outputs/noncommodity (accessed 16 September 2016)
[22] The authors report data for 2000 and 2010. Water requirements values for 2004 were determined through interpolation by assuming a linear growth.

6.5.3. Limitations and uncertainties

CGE results can only provide macro-regional averages as opposed to spatially-detailed models. The IWA indicator thus presents the trends of irrigation pressure from a global perspective by adding the market signals for factor allocation and international trade that spatially-detailed models are not able to embed. Hence, even within regions that appear to have enough resources to meet the future demand for irrigation water, there may be areas that will suffer from increased stress. These areas can be entire countries which are currently bundled in macro-regions in the disaggregated GTAP database (e.g. Mauritania, Niger), or river basins within large countries (e.g. North of China, West of Brazil, the Murray-Darling basin in Australia).

Land conversion possibilities could be an important factor in determining future irrigation requirements. Given that yields on irrigated land can be superior to those on rainfed, a more relaxed conversion of rainfed to irrigated land to meet the increases in crop demand could lead to higher irrigation water withdrawals. Therefore, to test the robustness of model results in relation to land conversion assumptions, a sensitivity analysis was run by varying the CET elasticity $\boldsymbol{\sigma_{AL}}$[23]. As expected, for most regions, a reduction in the elasticity leads to a reduction in withdrawals as a marker of increased friction in converting rainfed land to irrigated land, whereas an increase in the elasticity value leads to higher withdrawals (Figure 6.11).

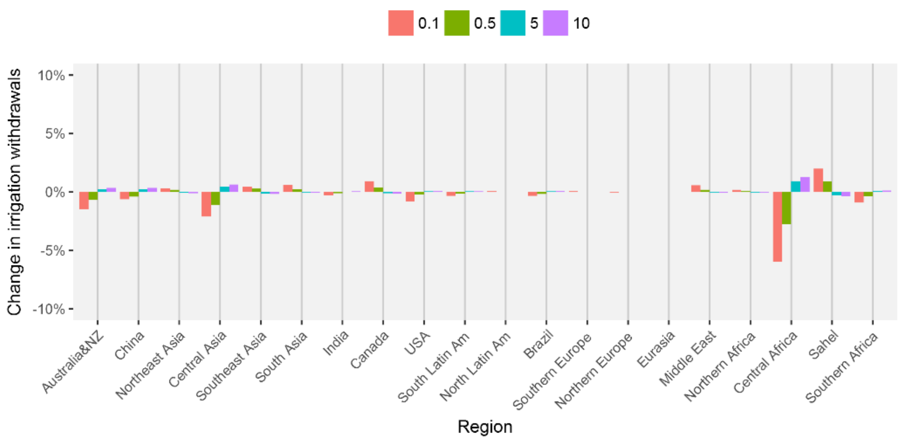

Figure 6.11 - Changes in regional irrigation withdrawals for 2050 – sensitivity analysis of cropland conversion elasticity

Note: the cases are determined by the different σ_{AL} values considered around the central value of 2. Changes indicate deviations from the withdrawal levels obtained in the central case for SSP2

[23] σ_{AL} is used to specify the conversion between rainfed and irrigated land – see equations 4.62 and 4.63 in Chapter 4 section 4.4.2.6.

Overall, irrigation withdrawal changes are nevertheless small and do not significantly influence the conclusions regarding the pressure of irrigation withdrawals across the RESCU-Water regions. These limited changes are particularly important for high elasticity values (**σ_{AL}=10**) where the largest increase is 1.3% (Central Africa), whilst water-scarce regions have negligible changes. Interestingly, a larger elasticity value leads to a decrease in water requirements in South Asia. This result is in line with the observation from the main results that, due to yield differentials between crop classes, the 'substitution' effect is strong and leads to more irrigation being used by water-efficient crops (veg&fruits) and less being used by water-intensive ones (*wheat*).

Some uncertainty associated with the water withdrawal results can be attributed to the way yield improvements are implemented in the production function of irrigated crops. Whilst yield improvements mean less land required for the same amount of output, it is not clear from the crop modelling literature whether this would also imply lower water requirements. Furthermore, farm-level studies show that there is a trade-off between yield and water productivity (see Cassman et al. 2015), i.e. a sub-unitary but positive elasticity of yield to water application. Therefore, for developing regions, it cannot be ascertained that closing down the current yield gaps will not imply additional irrigation water per hectare. This is even less clear for industrialised regions in which higher yields will come from further R&D with possibly unknown implications over beneficial water use. Throughout this thesis, the RESCU-Water model assumes that yield improvements on irrigated land impact both land and water inputs in the same way, however, more research should be dedicated to modelling yield as a function of water input[24].

The yield changes applied reflect inherent productivity gains and rule out climate change effects. Hence, by using multiple SSPs to address the range of possible socioeconomic development pathways, the results reflect the isolated contribution of income and population growth to changes in irrigation withdrawals pressure under expected technological advances and by assuming conditions of perfect climate change mitigation. There is high uncertainty with regard to climate change incidence over local-level mean climatic conditions and yields (see for instance Nelson et al. 2014 and Schewe et al. 2014). This topic is addressed in the next chapter by considering multi-model yield and water productivity impact information across different climate scenarios.

[24] See Mueller et al. (2012) for a spatial analysis of nutrient and freshwater requirements for closing yield gaps.

Recent work in Popp et al. (2017) explore the implications of the SSP narratives on land-use change through the consideration of other drivers in addition to income and population (technological change, international trade, dietary changes and environmental impacts), with the IMAGE model also considering changes in irrigation efficiency depending on the SSP choice. The results in this chapter regarding land-use change and irrigation water demand as a function of SSP are thus limited to the income and population effects, with one common technological advancement trajectory across the three development pathways. Considering the importance of yield improvements in the outcomes for water requirements, additional work could be dedicated to a wider translation of the SSP narratives in the model simulations in this area. This limitation is particularly applicable to the SSP1 storyline which implies a more rapid technological convergence between developed and developing regions.

6.6. Conclusions

In this chapter, an in-depth analysis of the evolution of resource pressure due to the expansion of blue water use in crop production at a global level was conducted using a CGE framework. Annual withdrawals up to 2050 were determined across a range of socioeconomic development futures complemented by expected inherent yield changes. Given the “bottom-up” specification of crop production systems, the effects captured comprise an overall change in irrigation demand stemming from crop demand expansion but also a substitution effect between the rainfed and irrigated varieties given yield differentials.

Throughout the 2004-2050 timeframe, an increase in withdrawals was obtained at a global level across all three SSP scenarios considered. The largest withdrawal changes will occur in developing regions (Central Africa, India, Northern Africa, Middle East) but also in the USA as a major crop producer and exporter. Regions that are already water-stressed will maintain and even expand their pressure causing potential bottlenecks, especially where non-crop sectors may increasingly compete for these resources. New areas (Central Asia) pass the IWA 20% threshold for water stress. China is the only region with extensive irrigation which sees a considerable decrease in blue water uses as a consequence of changes in the crop production mix in the region.

The SSPs with higher income growth for developing regions (SSP1 and SSP5) produce larger withdrawal results. Therefore, SSP1, also labelled as the 'sustainability' pathway, leads to more pressure from irrigation than the ‘middle of the road’ SSP2. These findings highlight the relationship between income and water uses in agriculture hinting towards the need for more efforts to improve irrigation water efficiency in crop production in order to determine a more sustainable use of freshwater resources. Therefore, a more detailed implementation of the SSP narratives covering yield improvements and irrigation efficiency in the RESCU-Water framework would enable a more comprehensive quantitative description of alternative water use futures. This is particulary important given that technological change proved to be as important as socioeconomic development in driving the future pressure over freshwater resources. The effects of yield improvements can have both a rebound effect leading to more irrigation withdrawals in some regions (India, Central Africa, USA), and reductive impact in other regions by improving regional water productivities in crop production (China, Northern Africa, Southeast Asia). Therefore an important determinant in the overall water requirements for the expected expansion in crop output will be the changes in relative yields between water-productive and water-intensive crops, but also the overall regional trends in cropland and water productivity.

Chapter 7. The impacts of higher CO_2 concentrations on global crop production and irrigation water requirements

7.1. Introduction

Anthropogenic climate change is expected to have a significant impact on agricultural output (Porter et al. 2014). The relationship between increases in concentrations of greenhouse gases (GHGs), CO_2 in particular, and crop growth is composed of multiple and possibly opposing effects (Gornall et al. 2010). On an annual basis, crop yields would be affected directly by changes in mean climatic conditions (temperature, precipitation, length of growing seasons) but also indirectly through the fertilisation effect of CO_2 due to the enhancement of photosynthesis of C3 plants[25].

From a water use perspective, CO_2 fertilisation (referred to in this chapter as CF) may also lead to higher crop water efficiencies through a lower transpiration at the leaf level (Wullschleger et al. 2002) and could thus appreciably alter water requirements for crop production (Betts et al. 2007). At the same time, changes in precipitation patterns would modify the natural soil water balance. As some areas are expected to have an increase in annual precipitation levels, the intensity of blue water usage on irrigated land to compensate for any soil moisture deficiencies for optimal crop growth could thus be reduced (Döll 2002; Fader et al. 2010; Gerten et al. 2011).

As explored in the previous chapter, crop demand growth due to socioeconomic development will lead to increases in irrigation water requirements in most regions. Therefore, the incidence of climate change will become more pronounced at a time with a growing pressure on freshwater resources coming from crop production. This conjunction of socioeconomic and climatic drivers of freshwater use indicate the importance of considering the implications of climate change on freshwater demand when analysing the economic impacts of future water deficits.

Many global economic models have been used to determine the effects of changes in mean climatic conditions over crop output. From a natural resource use perspective, most analyses have focused on the land-use change dimension and less on the implications for water requirements in crop production (Nelson et al. 2014; Wiebe et al. 2015; Fischer et al. 2005;

[25] C3 and C4 plants use different processes for carbon fixation through photosynthesis. C3 plants have a lower CO_2 absorption efficiency, hence the importance of ambient CO_2 concentrations for the plant's development. Whilst most plants belong to the C3 category, the most important examples of C4 crops are maize and sugarcane.

Palatnik & Roson 2011; Darwin et al. 1995). Furthermore, the effect of CF has not always been taken into account (Porter et al. 2014) despite its potentially non-negligible implications over irrigation water requirements and land use. The main deterrent to considering CF in economic models is the uncertainty of the extent to which this effect will materialise given its non-linear interactions with other factors – climatic (temperature, humidity) and concentrations of other GHGs (ozone precursors). Whilst laboratory trials have so far indicated the enhancing effect of higher CO_2 concentrations over yields, large-scale experiments are still under development. Nevertheless, global crop models are increasingly integrating this effect in relation to yields and crop water productivity (see Deryng et al. 2016).

In this chapter, crop modelling data is used to explore the additional dimension of CF in the relationship between climate change, crop production and irrigation water requirements through an economy-wide modelling framework. Changes in yields and irrigation water intensities are determined from the LPJmL crop model published through the ISIMIP Fast Track (Warszawski et al. 2014) for the two fertilisation variants (with and without CF) across two RCPs (2.6 and 8.5). These key parameters are calculated using climate data from three global circulation models (GCMs). The alterations to crop performance are then applied to the RESCU-Water model to measure deviations of global crop output and water requirements compared to a baseline calibrated onto the SSP2 "middle-of-the-road" pathway in the 2004-2050 timeframe. Crop production in the RESCU-Water model distinguishes between the rainfed and irrigated growing methods. This detailed representation of crop production systems enables the differentiation of climate change incidence across crops and between the two growing methods.

The chapter is composed of six sections. Section 7.2 reviews the extent to which irrigation water requirements have been a focal point in past climate change assessments using global economy-wide models. Section 7.3 details the crop model data used and the RESCU-Water model configuration and scenarios. Results covering crop output impacts, changes in irrigation water requirements and alterations to crop water productivities are presented in section 7.4 followed by a brief discussion in section 7.2. Section 7.3 concludes.

7.2. Climate change and irrigation water in CGE models

The incidence of climate change over crop production has been studied widely using CGE models. The opportunity of using this type of modelling framework comes from the multi-factor and multi-sectoral representation of the economy. Crop production is typically detailed through several crop types, hence, the impacts of climate change can be captured distinctly through crop-specific alterations to production conditions.

A first attempt to add the water dimension in the assessment of climate change impacts through a CGE framework is made in Fischer et al. (2007) using the BLS model (see Chapter 3 section 3.3.2.2). The authors focus on irrigation water requirements given crop water deficits induced by changes in soil water balances. Water requirements are thus calculated as a function of regional blue water intensities and irrigated cropland in use. The water intensities determined in the biophysical AEZ model are influenced by temperature and precipitation and do not consider CF, whilst the cropland expansion is induced by the growth in crop demand coming from socioeconomic development (SRES A2r scenario). The BLS-AEZ water requirements calculations under climate change suffer from some limitations. First, only soil moisture impacts are accounted for without any consideration of yield changes which could have important consequences over land and water use intensification. Second, irrigated production is treated exogenously as a share of total crop output with values derived from FAO projections. Therefore the substitution effects between rainfed and irrigated production as explored in the previous chapter cannot be captured. Third, irrigation water demand by crop type is not treated separately to include the variations in water intensities across crop classes but only follows a regional aggregate.

Climate change has also been a central topic in some of the global CGE models treating irrigation as a distinct factor of production (GTAP-W2 and GTAP-BIO-W). Calzadilla et al. (2013) use GTAP-W2 to analyse the impacts of climate change on crop output and welfare in 2020 and 2050 for the SRES A1B and A2 scenarios. Crop yields are embedded as a function of precipitation, CF and temperature whilst irrigation and land supply depend on river flow and rainfed land soil moisture respectively. In Calzadilla et al. (2011b) the model is further used to measure the compounded effects of climate change and the Doha Round trade tariffs.

Taheripour et al. (2013) assess the crop production and land-use impacts of climate change in the limited 2001-2021 time frame using GTAP-BIO-W. However, the assumptions made are over-simplifying and do not address any of the uncertainties related to climate change incidence – yield impacts are an extrapolation of the observed changes over the 1980-2008 period, whilst CF has a positive and uniform impact of yield without considering any differences between crop types.

As mentioned previously, a common specification in the GTAP-W2 and the GTAP-BIO-W models is the exogenous supply of irrigation. For GTAP-W2, the irrigation supply is linked to the changes in river flow as calculated by hydrological models[26]. GTAP-BIO-W adjusts the irrigation water availability based on the Irrigation Water Reliability Index from the IMPACT model (Rosegrant et al. 2012) which uses the value of total renewable water resources (TRWR) as a reference point. By deciding the regional water availability for agriculture outside the model framework, it is not possible to calculate any change in irrigation water requirements given climate-induced changes in yields and water intensities. Instead, the applications of these models capture the economic impacts of water scarcity using the perspective of changes in blue water availability.

An important recent work in assessing the climate change impacts on crop production employing global economic modelling is done in Nelson et al. (2014) through the use of the AgMIP models[27] (Rosenzweig et al. 2013). The common biophysical shocks (yield changes) address the uncertainty of climate change impacts at three distinct levels – climatic, agronomic and economic. Therefore multiple models are used at each level (GCMs, crop models and economic models). The emphasis is placed on the response differences between economic models in relation to crop output, prices, yields and cropland area expansion up to 2050. Changes in crop demand due to socioeconomic development are also considered through the use of the central SSP2 scenario. As only two of the nine economic models consider water as an input to crop production (PE models IMPACT[28] and MAgPIE and none of the CGE models), the impacts of climate change on irrigation water demand are not addressed.

7.3. Methods and data

7.3.1. Climate impacts data

Climate change impacts in this work are considered through two main channels –*yields* differentiated by crop class and by growing method (rainfed and irrigated), and *irrigation water intensities* by irrigated crop class. Changes in these two parameter sets are determined using the LPJmL crop model output with data published on the ISIMIP FastTrack platform[29]. The choice of LPJmL among all participating crop models in the inter-comparison project was based on the largest coverage of scenarios in terms of crop classes, RCPs and CF variants. The LPJmL yields and water data are calculated at a global level on an annual basis using a 0.5° spatial resolution

[26] This is only a partial incorporation of climate change impacts over water availability as it does not include changes in groundwater flows.
[27] Five CGE and four PE models
[28] Changes in crop water demand were determined only in Nelson et al. (2010) using the IMPACT model, however, the calculations already include water availability constraints due other water users, whilst the CO_2 fertilisation effect is capped at a low CO_2 concentration level (369ppm).

[29] https://esg.pik-potsdam.de/search/isimip-ft/ accessed 15 October 2016

and are based on changes in soil water balances and crop growing conditions (climatic and through CF).

The crop model output is expressed in values per hectare and reflects the conditions in each grid cell without taking into account actual crop production levels. Therefore, changes at a regional level are determined as averages by factoring in crop growing maps from MIRCA2000 (Portmann et al. 2010).

Yields per LPJmL crop class *crop*, growing method *m* and region *r* are calculated using the following weighted average:

$$Y_{r,crop,m}^{t} = \frac{\sum_{p_r} area_{crop,p_r,m} * yield_{crop,p_r,m}^{t}}{\sum_{p_r} prod_{crop,p_r,m}} \tag{7.1}$$

where p_r represent all the grid-cells within each RESCU-Water region *r*. Harvested area for each crop LPJmL crop class $area_{crop,p_r}$ is taken from the MIRCA2000 dataset whilst annual yield data $yield_{crop,p_r}^{t}$ is determined by LPJmL.

Water intensities are calculated by tracking the changes of the LPJmL *potential irrigation water withdrawal* $pirrww_{irc,p_r,m}^{t}$ variable of each crop type and for each region. The regional aggregation is done in a similar fashion as for yields:

$$PIRRWW_{r,crop}^{t} = \frac{\sum_{p_r} area_{crop,p_r} * pirrww_{crop,p_r}^{t}}{\sum_{p_r} prod_{crop,p_r}} \tag{7.2}$$

7.3.2. Data integration

Eleven crop types included in the LPJmL simulations were selected to determine the changes in two biophysical parameters (yields and water intensities) for the eight RESCU-Water crop types (see mapping in Table 7.1). Whilst the mapping is one to one for some crop types (wheat, rice and soy[30]), other crops need more detail due to the differences in climatic areas. For the GTAP *cane&beet* crop class, changes are considered for sugar beet in temperate RESCU-Water regions and sugarcane in tropical regions. The same for *other grains* – maize for temperate regions, millet for tropical regions. The regional aggregation of crop parameters using equations (7.1) and (7.2) for these eleven crops was done using the LPJmL-MIRCA2000 crop mapping in Table 7.2.

[30] Soy is the only crop type included in the ISIMIP Fast Track data which can be considered as an oil seed

Table 7.1 - RESCU-Water - LPJmL crop mapping

Application	RESCU-Water crop	LPJmL crop
Wheat	Wheat	Wheat
Paddy rice	Rice	Rice
Other grains tropical	Other grains	Millet
Other grains temperate	Other grains	Maize
Veg&fruits tropical	Veg&fruits	Cassava
Veg&fruits temperate	Veg&fruits	Field Pea
Cane and beet temperate	Cane&beet	Sugar Beet
Cane and beet tropical	Cane&beet	Sugarcane
Oil seeds	Oil seeds	Soy
Plant fibers	Fiber plants	Managed Grass
Other crops	Other crops	Weighted average of the above crops

Table 7.2 - LPJmL - MIRCA2000 crop mapping

LPJmL crop	MIRCA crop class	
Wheat	1	Wheat
Maize	2	Maize
Rice	3	Rice
Millet	6	Millet
Soy	8	Soybeans
Cassava	11	Cassava
Sugarcane	12	Sugar cane
Sugar Beet	13	Sugar beet
Rapeseed	15	Rapeseed
Managed Grass	25	Managed grassland
Field Pea	26	Others (annual)

To address the issue of climate change incidence uncertainty, the crop model data were considered in relation to the climate data of three GCMs (MIROC-ESM-CHEM, HadGEM-ES, IPSL-CM5). Also, to filter the effects of climate variability on model results, a two-sided 21-year moving average was used for both biophysical parameters. The simulation period for RESCU-Water being 2004-2050, the LPJmL data considered covers thus the 1994-2060 timeframe. Yield and irrigation water intensity data are implemented as regional productivity changes of the land inputs and water uses respectively.

The overall data integration process is illustrated in Figure 7.1. The ISIMIP data as outputs of the LPJmL data are considered separately for each of three GCMs. The aggregation to a regional level and the climatic variability filtering are conducted using a script developed in R. The productivity changes are calculated annually[31]:

$$\Delta\bar{Y}^{t}_{r,crop,m} = \frac{\bar{Y}^{t}_{r,crop,m}}{\bar{Y}^{t-1}_{r,crop,m}} \tag{7.3}$$

$$\Delta\overline{PIRRWW}^{t}_{r,irc} = \frac{\overline{PIRRWW}^{t}_{r,irc}}{\overline{PIRRWW}^{t-1}_{r,irc}} \tag{7.4}$$

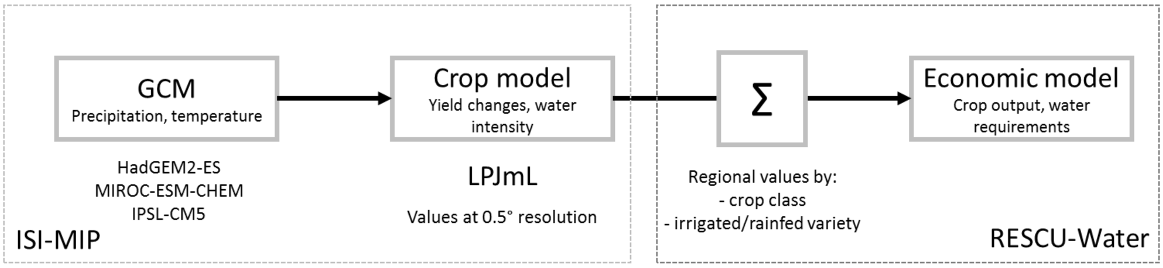

Figure 7.1 - Crop data treatment and integration

In the RESCU-Water model, yield changes $\Delta\bar{Y}^{t}_{r,crop,m}$ are then specified through modifications to the $\lambda_{RfLand,crop}$ and $\lambda_{Irr\text{-}Land,crop}$ efficiency parameters for rainfed and irrigated land inputs respectively (see equation (7.5) for irrigated crops). Similarly to Chapter 6, the baseline values for λ reflect the expected technological advancements as calculated by the IMPACT model (Nelson et al. 2010) and correspond to conditions of perfect climate change mitigation. The irrigation water intensity changes modify the blue water intensity parameters $\phi_{irc,Water}$ of irrigated crops. The identity equation (6.1) in Chapter 6 corresponding to water uses by crop type is updated to reflect these changes (equation (7.6)).

$$\lambda^{cc}_{IrrLand,crop,t} = \Delta\bar{Y}^{t}_{r,crop,IrrLand} * \lambda^{base}_{IrrLand,crop} \tag{7.5}$$

$$EXF^{irc,t}_{Water} = \Delta\overline{PIRRWW}^{t}{}_{r,irc} * \phi_{irc,Water} * \quad XF^{irc,t}_{Irrigation} \tag{7.6}$$

The results of the data aggregation outlined above are presented in Figure 7.2 by comparing yield and water intensity changes across the two CF variants. Without CF, yields are generally lower (points left of the y-axis) and this tendency is amplified with the growth in CO_2 concentrations (RCP8.5). Crop water intensities outcomes are mixed for RCP2.6 (points on both sides of the y-axis). However, a general increase in intensity is observed with RCP8.5. With CF, yields obtain a net improvement (points above the x-axis) which is increasing with CO_2

[31] This calculation is different to the approach taken in Nelson et al. (2014) where yield changes evolve linearly from the values in the base year to the values in 2050.

concentrations. At the same time, some crops (C4) are indifferent to the fertilisation effect in terms of yield changes (points on the diagonal). This indifference is not applicable to water intensities as the CF-induced water efficiency is found in both C3 and C4 crop types (all points are below the diagonal indicating lower water intensities *with CF* compared to *without CF* for all crops in all regions).

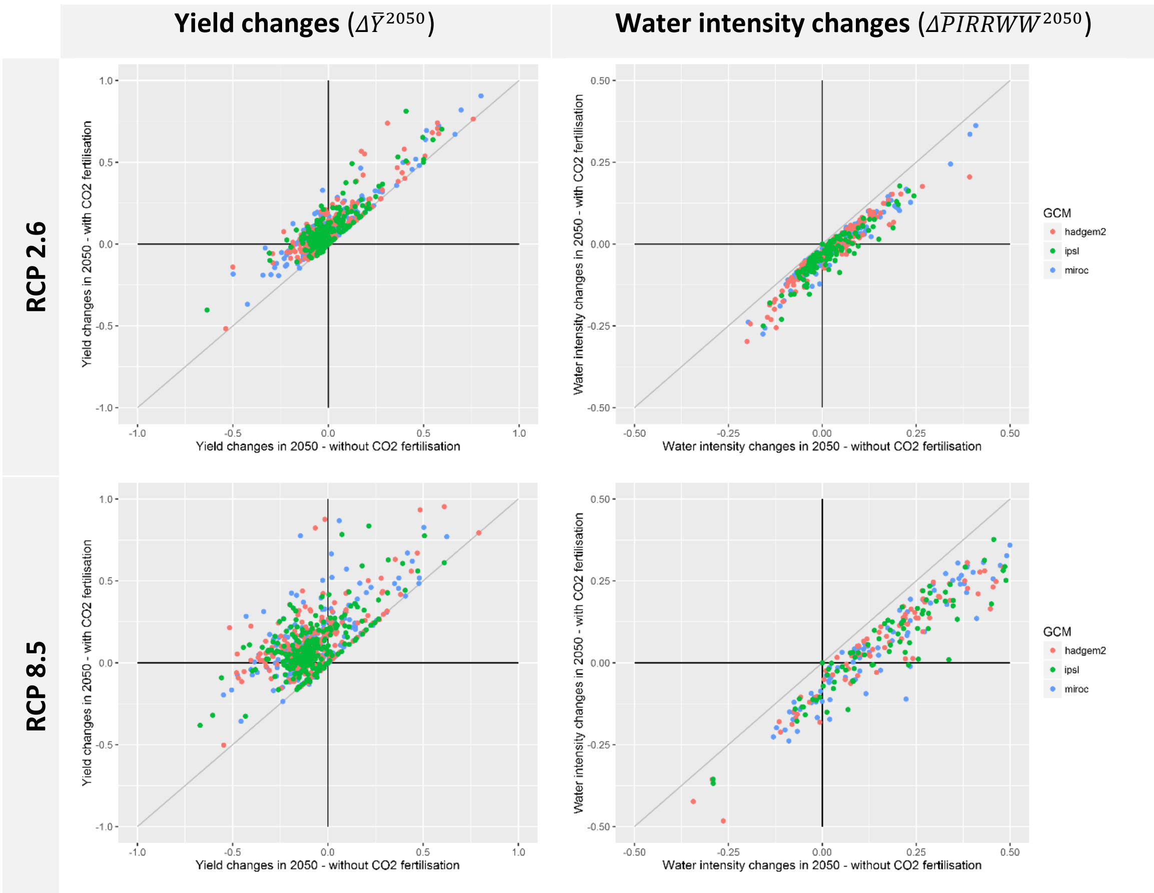

Figure 7.2 - Comparison of yield and irrigation water intensity changes between CO_2 fertilisation variants and across GCMs

Note: Each point represents one crop variety (by crop class and growing method) within one RESCU-Water region

7.3.3. Model configuration and scenarios

The configuration of the economic model and the irrigation water use assumptions are the same as in Chapter 6:

- The supply of irrigation is endogenous allowing for a contraction or expansion as a function of market price signals.
- Land is supplied through a two-stage CET function.
- Water demand in irrigation is not an independent model variable but calculated through the identity equation (6.1) from Chapter 6.

- Socioeconomic development is included through changes in capital and labour supply; regional GDP growth rates are achieved through an endogenous labour productivity parameter; the LES demand system is updated to account for changes in regional subsistence consumption coming from population growth.
- Regional water uses are a measure of water requirements and indicate future pressure over the resource base under different climate change assumptions.

The model results are compared across the lowest (RCP2.6) and highest (RCP8.5) radiative forcing scenarios. CO_2 concentrations in the full range of RCPs start to significantly diverge from 2025 and lead to a 100ppm span by 2050 (Figure 7.3). Therefore, when getting closer to the end of the simulation period, in addition to changes in climatic conditions, the size of the CF effect becomes increasingly sensitive to the concentration pathway choice.

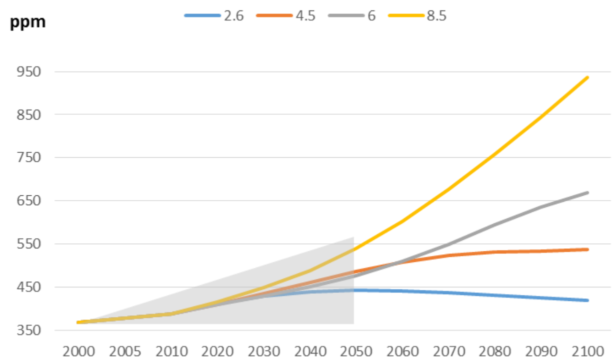

Figure 7.3 - CO_2 concentrations 2000-2100 by RCP.

Source: RCP database http://www.iiasa.ac.at/web-apps/tnt/RcpDb, last accessed 17 October 2016. Concentrations are determined by the IMAGE, MiniCAM, AIM, MESSAGE models for RCP 2.6, 4.5, 6.0 and 8.5 respectively, and exclude the CO_2e concentrations of other GHG.

Socioeconomic development is included through the SSP2 "middle of the road" storyline. Emission patterns for the SSP2 socioeconomic scenario are projected in van Vuuren et al. (2014) to determine radiative forcing levels in the RCP6.0-RCP8.5 range. However, the lower RCP2.6 is included in order to explore the implications of climate action on crop output and irrigation water requirements.

Yield and water intensity changes are considered for both CF variants (with and without CF) in each RCP scenario (see scenario outline in Table 7.3). Changes in the two parameter sets corresponding to climate data of each of the three GCMs considered are included through separate RESCU-Water model runs. The results for the main scenarios are reported however as averages across the three circulation models.

Table 7.3 - Simulation scenarios

Scenario number	Label	RCP	SSP	CF variant	GCM
(1)	**Baseline**	No climate change	SSP2	n/a	None
(2.1)	**RCP 2.6 w/o CF**	RCP 2.6	SSP2 calibration	No CO_2 fertilisation	HADGEM2 IPSL MIROC
(2.2)	**RCP 2.6 CF**			With CO_2 fertilisation	
(3.1)	**RCP 8.5 w/o CF**	RCP 8.5		No CO_2 fertilisation	
(3.2)	**RCP 8.5 CF**			With CO_2 fertilisation	

It should be noted that only yields act as shock variables in the RESCU-Water simulations. These shocks determine a new equilibrium point through a change in the cost structure of crop production – a reduction in yields leads to higher costs of production due to higher land input requirements. The corresponding change in land and irrigation demand[32] lead to an overall crop cost effect but also to a substitution of these land and irrigation in relation to the other inputs to crop production. In contrast, the water intensities indicate the levels of water required by the use of the *Irrigation* factor across crops, but do not affect the supply and allocation of irrigation or cropland.

7.4. Results

7.4.1. Global impacts

In 2050, changes in crop growing conditions have a visible impact on crop sectors even for the low emissions pathway RCP2.6. Deviations from the baseline and the variance of climate change incidence across regions increase with CO_2 concentrations. Figure 7.4 shows the changes relative to the baseline equilibrium in 2050 to the main market variables related to crops (price, output and exports) and resource use (water requirements and arable land). The boxplots illustrate the combined results across crop types and regions.

The cost effect of the yield evolution is noticeable through changes in crop market prices. The results show opposing impacts of the two CF variants. Whilst climate change increases prices and determines a reduction in crop output when CF is not considered, fertilisation more than offsets the loss of yields induced by climatic conditions, leading to an overall crop price decrease

[32] Irrigable land and irrigation are specified as perfect complements – see Chapter 4 section 4.4.2.1.

and a boost to crop production compared to the baseline. The size of international trade of crops measured through regional exports changes in the same direction as crop output. Nevertheless, the variance between regions is lower when CF is embedded indicating that the addition of fertilisation narrows down the differences in prices and output levels across crops and regions. The water productivity changes represented are endogenous to the economic model. These reflect the evolution of water intensities as calculated by the LPJmL model, but also include the alterations to the allocation of the *Irrigation* factor given the input substitution effect and changes in the crop production mix.

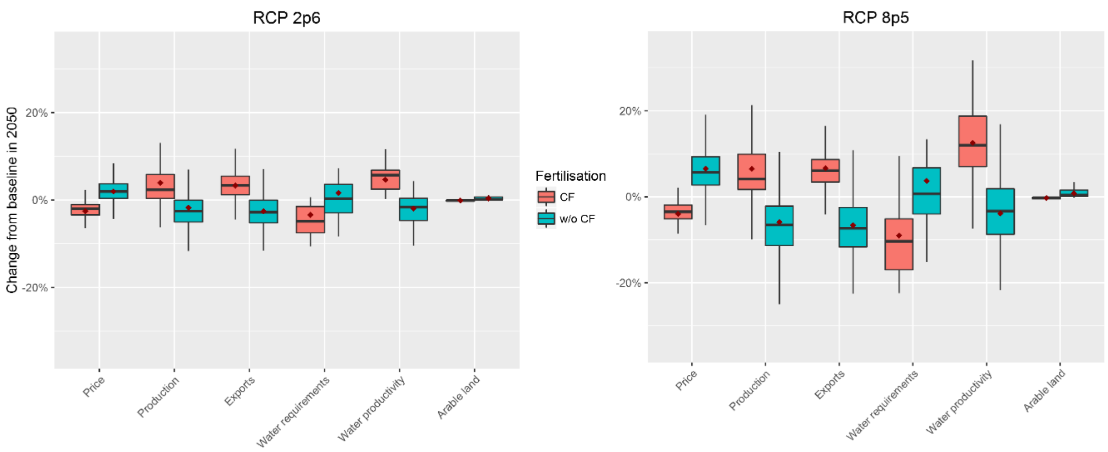

Figure 7.4 - RCP 2.6 and RCP 8.5 changes in main crop variables (% change from 2050 baseline values)

Note: the whiskers and boxes indicate the 5th, 25th, 50th, 75th and 95th percentiles. The diamonds represent the mean values.

The regional changes in crop production and irrigation water requirements are presented in Table 7.4. Without CF, regional crop production generally decreases with many cases in which total withdrawals increase. Nevertheless, with the exception of China, these regions have a small share in global withdrawals. In several irrigation-intensive regions (India, South Asia, USA, Middle East and Northern Africa) the decrease in crop production has a dominant effect over total withdrawals (an effect amplifying with the increase in GHG concentrations) lowering the regional irrigation water requirements.

Regional crop water productivities (CWP), calculated as the ratio between total irrigated crop outputs to regional irrigation water requirements, are also decreasing with a few exceptions. With CF, regional crop production virtually grows in every region. This growth is accompanied by significant increases in CWP that lead to an overall reduction in regional water requirements.

Table 7.4 - Regional changes in crop production, irrigation withdrawals and crop water productivity in 2050 relative to the baseline

RESCU-Water region	RCP 2.6						RCP 8.5					
	no CF			CF			no CF			CF		
	PROD	W	CWP	PROD	W	CWP	PROD	W	CWP	PROD	W	CWP
Australia&NZ	(1.4%)	2.1%	(3.4%)	3.1%	0.2%	2.9%	(4.5%)	2.2%	(6.6%)	5.3%	(2.6%)	8.2%
China	(2.7%)	14.3%	(14.8%)	5.1%	11.0%	(5.4%)	(7.1%)	11.2%	(16.4%)	10.1%	2.8%	7.1%
Northeast Asia	0.1%	17.9%	(15.1%)	3.3%	11.3%	(7.2%)	(1.2%)	32.6%	(25.5%)	5.7%	15.0%	(8.1%)
Central Asia	(1.6%)	0.5%	(2.1%)	5.1%	(3.4%)	8.7%	(7.6%)	5.9%	(12.7%)	7.5%	(4.6%)	12.6%
Southeast Asia	(7.5%)	(0.3%)	(7.2%)	2.2%	(3.8%)	6.3%	(16.6%)	0.0%	(16.6%)	4.4%	(9.3%)	15.1%
South Asia	(5.4%)	(5.6%)	0.2%	1.0%	(7.6%)	9.3%	(11.4%)	(11.6%)	0.2%	1.6%	(16.6%)	21.7%
India	(1.7%)	(5.8%)	4.4%	9.9%	(7.4%)	18.7%	(14.8%)	(15.1%)	0.5%	9.0%	(18.3%)	33.3%
Canada	(4.3%)	(8.3%)	4.4%	(0.1%)	(9.1%)	9.9%	(5.1%)	(10.2%)	5.7%	3.7%	(13.5%)	19.8%
USA	(2.9%)	(2.8%)	(0.1%)	2.0%	(6.3%)	8.9%	(7.8%)	(2.6%)	(5.3%)	3.4%	(11.4%)	16.7%
S Latin America	(5.9%)	2.9%	(8.5%)	1.5%	(1.6%)	3.2%	(10.1%)	2.4%	(12.2%)	6.9%	(7.6%)	15.7%
N Latin America	(2.7%)	(0.9%)	(1.8%)	3.8%	(1.9%)	5.8%	(6.6%)	(1.9%)	(4.8%)	7.3%	(5.9%)	14.0%
Brazil	(3.2%)	0.2%	(3.3%)	2.6%	(6.3%)	9.5%	(9.2%)	(3.6%)	(5.8%)	4.0%	(18.5%)	27.6%
Southern Europe	(2.7%)	7.3%	(9.3%)	(0.3%)	0.7%	(1.0%)	(5.1%)	9.4%	(13.3%)	0.1%	(6.4%)	6.9%
Northern Europe	4.3%	14.2%	(8.7%)	5.1%	(1.0%)	6.1%	3.6%	52.7%	(32.1%)	5.8%	9.5%	(3.4%)
Eurasia	(2.3%)	(4.6%)	2.4%	2.0%	(10.5%)	14.1%	(6.5%)	(5.3%)	(1.3%)	3.2%	(19.0%)	27.3%
Middle East	(4.2%)	(1.8%)	(2.4%)	(0.7%)	(5.9%)	5.5%	(5.7%)	(3.0%)	(2.8%)	2.1%	(13.3%)	17.8%
Northern Africa	(2.4%)	(3.3%)	0.9%	(0.0%)	(7.4%)	7.9%	(3.9%)	(5.9%)	2.1%	1.0%	(14.9%)	18.6%
Central Africa	(5.3%)	5.7%	(10.4%)	0.8%	(8.0%)	9.5%	(10.9%)	13.4%	(21.4%)	2.4%	(22.4%)	32.0%
Sahel	(4.0%)	1.0%	(5.0%)	0.1%	(8.4%)	9.3%	(7.8%)	1.4%	(9.1%)	1.4%	(18.1%)	23.9%
S Africa	(1.2%)	0.5%	(1.6%)	2.4%	(2.1%)	4.6%	(3.0%)	(3.0%)	0.0%	4.8%	(5.3%)	10.6%

PROD = regional crop production, W = regional irrigation water requirements, CWP = regional crop water productivity

7.1.1. Changes in water requirements

Global water requirements decline with the increase in CO_2 concentrations in both CF variants. Without the CF effect, requirements in 2050 are 1.1% and 5% lower for RCP2.6 and RCP8.5 respectively compared to the baseline (Figure 7.5). This decline is primarily due to the overall decrease in crop production. However, part of this effect is counter-balanced by a reduction in irrigation water productivity in many regions. At the same time, despite the expansion in crop output, CF determines an even higher reduction in water requirements - 4.1% (RCP2.6) and 12.2% (RCP8.5).

Table 7.5 shows changes in withdrawals by ordering the RESCU-Water regions by the baseline freshwater resource pressure coming from irrigation (result from Chapter 6 for SSP2). Water productivity with CF increases significantly in most areas including irrigation-intensive regions such as India, Middle East, Northern Africa and the USA. These productivity changes offset the implied growth of demand in irrigation water coming from the baseline expansion in crop production and determine an overall decrease in withdrawals. China, Northeast Asia and Northern Europe are the only regions to face an increase in water pressure across all scenarios, whilst some other regions are adversely affected only when CF is not considered (e.g. Central Asia, Southern Europe, Southern Africa, Australia&NZ).

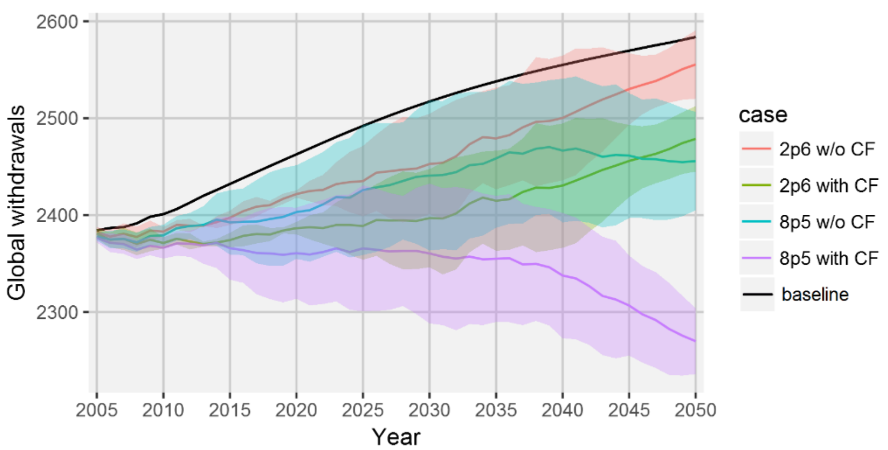

Figure 7.5 - Global irrigation water withdrawals by climate change scenario - 2005-2050 (in km^3)

Note: the lines represent the mean values obtained across the three GCMs, the ribbons indicate the standard deviation.

Table 7.5 - Changes in regional irrigation water withdrawals in 2050 relative to the baseline

Regions	Baseline	no CF		CF	
	2050 IWA	RCP2.6	RCP8.5	RCP2.6	RCP8.5
South Asia	1.03	-6%	-12%	-8%	-17%
Northern Africa	0.88	-3%	-6%	-7%	-15%
Middle East	0.62	-2%	-3%	-6%	-13%
India	0.42	-6%	-15%	-7%	-18%
Central Asia	0.20	0%	6%	-3%	-5%
China	0.10	14%	11%	11%	3%
USA	0.08	-3%	-3%	-6%	-11%
Southern Europe	0.07	7%	9%	1%	-6%
Southern Africa	0.06	0%	2%	-2%	-5%
SE Asia	0.03	0%	0%	-4%	-9%
Australia&NZ	0.02	2%	3%	1%	-3%
NE Asia	0.02	18%	33%	11%	15%
North Latin Am	0.01	-1%	-2%	-2%	-6%
South Latin Am	0.01	2%	2%	-2%	-8%
Sahel	0.01	1%	1%	-8%	-18%
Central Africa	0.01	5%	13%	-9%	-23%
Eurasia	0.00	-5%	-5%	-12%	-19%
Brazil	0.00	0%	-7%	-7%	-21%
Northern Europe	0.00	14%	57%	0%	14%
Canada	0.00	-9%	-13%	-8%	-10%
World		**-1%**	**-5%**	**-4%**	**-12%**

The global changes in irrigation water requirements are thus concentrated in irrigation-intensive regions (Table 7.6). In RCP8.5, the reductions in India account for more than a third of the world total with CF, and almost for all global reductions without CF (see Table B1 in Annex B). South Asia, Middle East and Northern Africa are also important drivers in decreasing the global water demand, whilst China increases water requirements for all crops but *wheat* and *cane&beet*. Across crops, the most significant decreases occur for *wheat* in both CF variants. At the same time, the largest contrasts are obtained for *veg&fruits* and *oil seeds* – a decrease in water requirements with CF and an increase without CF. These classes are also high-value crops determining a re-allocation of irrigation away from other types when adapting to the incidence of climate change.

7.1.2. Crop-specific impacts

Several differences emerge between crop types in both CF variants. When CF is not factored in, regional crop output generally decreases with climate change and is accompanied by crop price inflation (see Figure B1 in Annex B). The highest negative impact occurs for *rice*, *wheat* and *oil seeds*, whilst *other grains* (maize and tropical coarse grains) are less affected. With CF embedded, the impacts are reversed as output compared to the baseline expands in most cases. For food crops, *rice* and *oil seeds* face the highest production growth, whereas *wheat*, *other grains* and *veg&fruits* are less sensitive to CF.

Table 7.6 - Changes in regional water requirements (in km^3) by crop type and by CO_2 fertilisation variant in 2050 relative to the baseline - RCP 8.5

Region	Overall		Wheat		Rice		Other grains		Veg&fruits		Fiber plants		Cane&beet		Oil seeds		Other crops	
	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF
Australia&NZ	(0.4)	0.3	(0.1)	(0.1)	(0.2)	(0.2)	(0.1)	(0.0)	(0.3)	(0.0)	0.4	0.6	0.0	(0.1)			(0.1)	0.3
Brazil	(2.1)	(0.4)	(0.0)	0.0	(0.9)	(0.5)	(0.0)	(0.0)	(0.6)	0.3	0.0	0.0	(0.2)	(0.3)	(0.0)	0.1	(0.3)	0.1
Sahel	(1.9)	0.1	(0.0)	(0.1)	(0.8)	0.9	(0.0)	(0.0)	(0.0)	(0.2)	(0.0)	0.0	(0.4)	(0.4)			(0.7)	(0.0)
Central Africa	(5.4)	3.2	(0.0)	(0.0)	(2.5)	3.6	0.4	0.4	(1.2)	0.2	(0.1)	(0.1)	(0.2)	(0.2)	(0.0)	0.0	(1.8)	(0.7)
Central Asia	(4.0)	5.1	(5.8)	(0.9)	(0.5)	(0.6)	(3.2)	(1.6)	(2.9)	(1.3)	8.5	10.1	(0.1)	(0.0)	0.0	0.0	(0.1)	(0.5)
China	8.4	33.7	(7.8)	(4.2)	13.8	15.0	3.0	9.1	(2.4)	6.3	1.4	2.8	(1.6)	(1.2)	1.9	6.0	0.1	0.0
Eurasia	(3.7)	(1.0)	(2.0)	(1.2)	(0.2)	(0.3)	(0.5)	0.3	(0.2)	0.5	(0.1)	0.5	0.0	0.1	(0.1)	(0.0)	(0.7)	(0.7)
India	(144.3)	(119.7)	(70.0)	(55.7)	(10.6)	(16.2)	(0.5)	(0.5)	(6.0)	12.2	(11.2)	(8.7)	(34.1)	(43.5)	(1.5)	2.8	(10.3)	(9.9)
Middle East	(34.2)	(7.7)	(8.5)	(6.9)	(1.0)	(0.7)	(1.6)	(0.6)	(18.3)	0.3	3.3	6.4	(0.4)	(0.5)	(0.9)	(0.3)	(6.8)	(5.3)
Northern Africa	(28.5)	(11.3)	(1.7)	(2.8)	(2.9)	(2.4)	(7.6)	(7.3)	(6.8)	0.2	4.2	4.7	(2.4)	(2.3)	(0.3)	(0.1)	(10.7)	(1.2)
Northeast Asia	1.4	3.0	(0.0)	0.0	1.1	2.5	(0.0)	0.1	(0.0)	0.1			0.0	0.0	0.2	0.2	0.1	0.1
Northern Europe	0.1	0.5	(0.0)	0.0			0.0	0.0	0.0	0.3			0.0	0.1			(0.0)	0.1
North Latin Am	(5.8)	(1.8)	(0.9)	(4.1)	0.3	(1.6)	0.3	0.8	(4.2)	0.9	0.6	0.6	(1.5)	(2.0)	(0.4)	4.2	(0.1)	(0.6)
Canada	(0.3)	(0.2)	(0.1)	(0.1)			0.0	0.0	(0.1)	0.1					(0.1)	(0.0)	(0.1)	(0.1)
Southern Africa	(0.7)	0.3	(0.0)	(0.3)	(0.0)	(0.0)	0.6	1.1	(0.2)	0.3	(0.0)	0.0	(0.5)	(0.6)	0.0	0.1	(0.5)	(0.4)
South Asia	(49.4)	(34.6)	(15.9)	(16.8)	(7.5)	(6.4)	(2.6)	(0.9)	(8.2)	(0.8)	(2.6)	(1.0)	(8.0)	(6.7)	(0.1)	0.3	(4.4)	(2.3)
Southeast Asia	(17.9)	0.0	(4.3)	(2.1)	(10.9)	(5.3)	0.0	0.0	1.5	7.9	(0.0)	0.0	(3.0)	(1.9)	(0.2)	(0.1)	(1.0)	1.6
Southern Europe	(4.2)	6.3	(0.6)	(0.3)	(0.2)	(0.1)	0.9	1.8	(4.1)	2.3	1.4	1.7	0.0	0.1	(0.6)	(0.1)	(1.0)	0.9
South Latin Am	(1.8)	0.5	(0.2)	(0.2)	(0.2)	(0.5)	0.3	0.8	(0.6)	(0.2)	0.1	0.0	(0.7)	(0.7)	(0.4)	1.5	(0.0)	(0.3)
USA	(19.5)	(4.4)	(4.6)	(4.6)	(0.4)	1.3	(4.5)	(4.4)	(3.5)	0.0	1.0	4.7	(0.3)	(0.3)	(6.6)	(0.7)	(0.7)	(0.5)
World	**(314.1)**	**(128.0)**	**(122.6)**	**(100.6)**	**(23.6)**	**(11.7)**	**(15.3)**	**(1.0)**	**(58.0)**	**28.9**	**7.0**	**22.4**	**(53.4)**	**(60.5)**	**(9.1)**	**13.7**	**(39.0)**	**(19.4)**

Table 7.7 - Changes in regional crop production by crop type and by growing method in 2050 relative to the baseline - RCP 8.5 without CO_2 fertilisation

Region	Wheat		Rice		Other grains		Veg&fruits		Fiber plants		Cane&beet		Oil seeds		Other crops	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
Australia&NZ	-19%	-4%	-13%	-50%	2%	-4%	-7%	-7%	5%	0%	35%	-30%	97%	-12%	19%	-20%
Brazil	-8%	-10%	-11%	-14%	-12%	-3%	2%	-9%	12%	-8%	-12%	6%	20%	-23%	1%	-9%
Sahel	-32%	-4%	-16%	2%	13%	-5%	5%	-6%	46%	62%	-13%	-9%	-24%	-16%	-19%	-7%
Central Africa	-65%	-24%	36%	-33%	89%	-7%	-7%	-13%	-43%	-6%	-63%	32%	74%	-20%	-12%	-11%
Central Asia	3%	-12%	-15%	34%	-3%	-4%	-18%	23%	12%	-27%	2%	-31%	16%	-49%	-16%	-25%
China	-10%	18%	-10%	-9%	11%	-17%	-1%	-14%	52%	-17%	-11%	61%	26%	-24%	-4%	-3%
Eurasia	-14%	-5%	-33%	34%	0%	-2%	4%	-9%	24%	-7%	-9%	-5%	-10%	-7%	-24%	3%
India	-16%	-37%	-8%	-85%	-9%	-7%	22%	-51%	-51%	48%	-61%	586%	48%	-31%	-29%	-4%
Middle East	-12%	-3%	-6%	102%	0%	-7%	-2%	-13%	18%	45%	-10%	-25%	-5%	15%	-12%	-9%
Northern Africa	-34%	-10%	-21%	-4%	20%	13%	-2%	-23%	8%	28%	0%	5%	212%	-54%	-6%	-7%
Northeast Asia	10%	13%	0%	-28%	14%	14%	-3%	-9%	10%	15%	7%	-4%	41%	24%	12%	-5%
Northern Europe	-21%	-2%	-3%	-91%	-51%	45%	-3%	-18%	-21%	-13%	12%	-46%	-2%	-2%	-3%	-15%
North Latin Am	-13%	-2%	88%	30%	9%	2%	9%	2%	6%	32%	7%	-3%	-26%	28%	13%	2%
Canada	-42%	-35%	15%	-52%	-9%	-5%	-16%	-6%	24%	-6%	-33%	41%	4%	-60%	-3%	-34%
Southern Africa	-20%	-53%	-14%	-89%	-4%	-22%	-3%	-11%	-11%	-12%	-28%	1303%	12%	-26%	-13%	-4%
South Asia	-20%	-1%	-18%	69%	51%	-23%	-10%	-10%	-11%	7%	24%	90%	52%	-26%	-3%	7%
Southeast Asia	-22%	-29%	-18%	-27%	-21%	-12%	6%	-17%	-4%	-3%	-33%	44%	-37%	-32%	-5%	-29%
Southern Europe	-27%	-9%	-5%	-2%	119%	-14%	-2%	64%	-15%	38%	26%	10%	60%	-21%	-7%	2%
South Latin Am	-9%	-7%	-6%	-7%	7%	-11%	2%	-9%	19%	-51%	-2%	-12%	-9%	-2%	5%	-18%
USA	-25%	2%	-7%	-30%	-14%	-11%	-3%	-4%	4%	-17%	-5%	3%	-7%	-17%	-9%	-10%
World	**-15%**	**-4%**	**-8%**	**-26%**	**5%**	**-6%**	**-1%**	**-14%**	**1%**	**-2%**	**-17%**	**21%**	**9%**	**-20%**	**-3%**	**-9%**

The incidence of climate change can also be differentiated by grouping regions into their preponderant climate type (Figure 7.6). Without CF, changes in climatic conditions alone have a stronger adverse impact on crop output in tropical regions. The *cane&beet* group is mostly positively affected by changes in climatic conditions. As a C4 crop, sugar cane is indifferent to CF, hence the fertilisation effect for *cane&beet* is more visible in temperate regions where sugar beets[33] are grown predominantly. Although the total effect on output relative to the baseline remains stronger in temperate regions, CF plays an important role in correcting some of the distributional effects of climate change on crop output. When CF is embedded, except for the *other grains* group, tropical regions have a higher incremental change in output across all crop classes (see Figure B2 in Annex B).

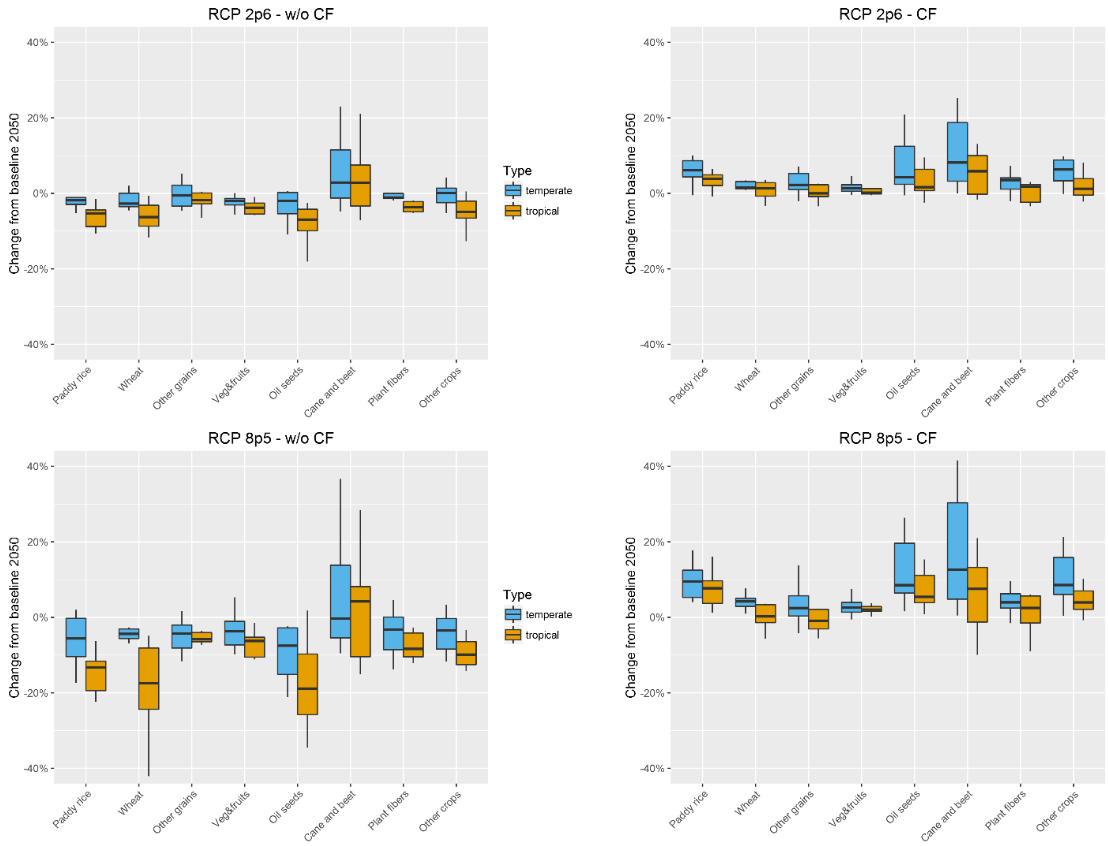

Figure 7.6 - Crop output changes by RCP and by CO2 fertilisation variant in 2050 relative to the baseline

Globally, without CF, the most affected crops are *wheat* and *rice* with decreases in output for both irrigated and rainfed production (Table 7.7). The drop in irrigated output indicates that the use of irrigation does not act as an adaptation measure to climate change for these crop types

[33] Sugar cane and sugar beets are bundled in the GTAP database, hence they are represented together in the model

due to their high irrigation intensities. As observed in the withdrawal change patterns in Table 7.6, irrigation is re-allocated from these crops to more irrigation-efficient ones as a consequence of alterations to yield differentials[34]. At the same time, due to more favourable growing conditions, *cane&beet* switch production from irrigated to rainfed. As for the other crop classes (*other grains*, *veg&fruits*, *fiber plants*, *oil seeds* and *other crops*), the weight of irrigated production in total crop output generally increases.

7.1.3. Decomposition of regional water productivity changes with CO_2 fertilisation

Changes in CWP with CF can be explained through the three main drivers: (1) water re-allocation across crop types through differentiated yield changes (endogenous), (2) changes in natural soil moisture of irrigated land (exogenous) and (3) fertilisation water efficiency gains from evapotranspiration (exogenous). The endogenous/exogenous distinction is made based on whether the driver determines or not a change to the RESCU-Water model solution and implicitly on whether it affects crop output and irrigation allocation.

The effects are calculated as follows:

- *Crop yield changes* – changes in water requirements relative to the baseline due to climate change impacts on yields but without changing the baseline water intensities
- *Soil moisture* – additional changes in water requirements by updating the water intensities to the "w/o CF" scenarios values. These reflect the changes in natural soil water balances when factoring in changes in climatic conditions
- *CF water efficiency* – additional changes in water requirements by further updating water intensities to "CF" scenarios values.

With CF embedded, CWP is higher than the baseline in all tropical regions, whereas the outcome is mixed for temperate areas as China and NE Asia continue to be negatively affected in both RCPs and Central Asia in RCP8.5. The water efficiency gains induced by CF increases CWP in all regions (Figure 7.7) and has the strongest impact among the three drivers in most cases. Hence this effect determines many regions to switch from a decline in water productivity to an increase, among which are India and USA - regions which account for an important share in world irrigation withdrawals.

A contrast emerges between tropical and temperate regions in which the impact of soil moisture over CWP is significant. Tropical areas generally benefit from higher soil moisture due to increases in precipitation requiring less irrigation water to compensate for soil water

[34] Yield changes equally influence the irrigation productivity due to the Leontief specification of land-related inputs in irrigated crop production

deficiencies. Nevertheless, this positive impact is entirely or partially offset in water-stressed regions (India, South Asia, Middle East, Northern Africa) through irrigation re-allocations to more water-intensive crops due to relative yield changes.

Another important observation is that the effects of CF-induced water efficiency and soil moisture over CWP increase with CO_2 concentrations. This amplification is also generally applicable to yield changes, except China, Eurasia, Southern Africa, USA and North Latin America where the yield impacts on CWP turn from positive to negative when moving from RCP2.6 to RCP8.5.

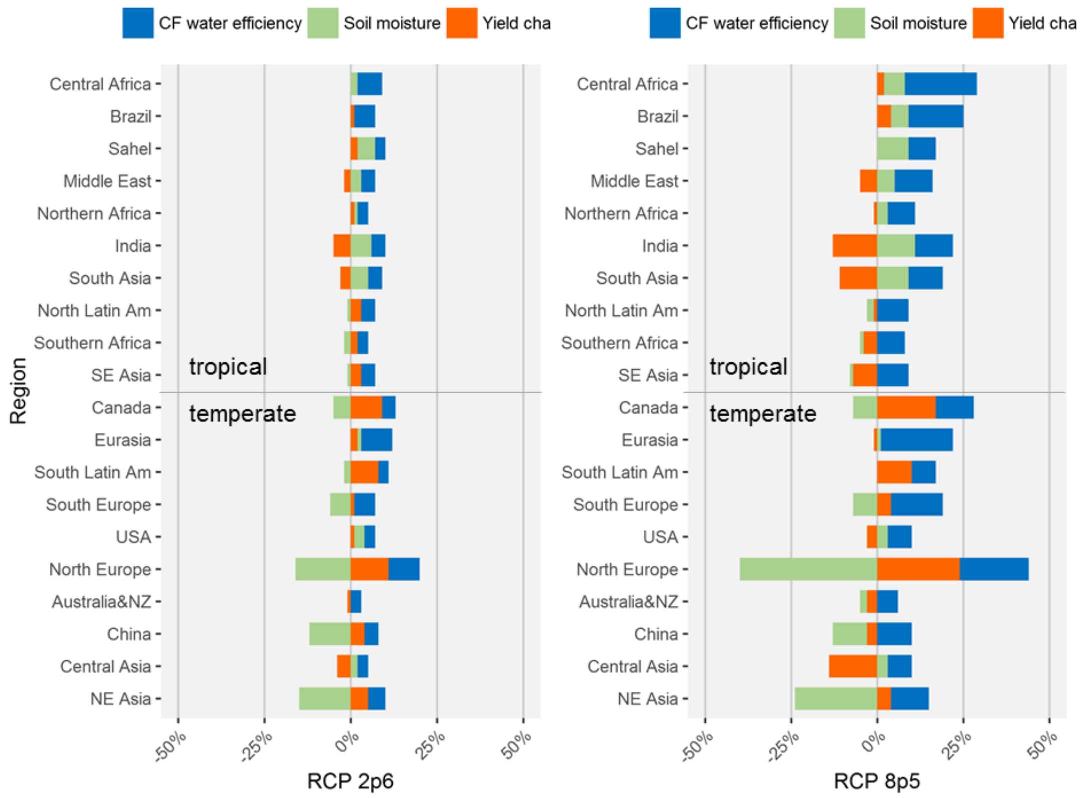

Figure 7.7 - Decomposition of water productivity changes for 2050 in scenarios with CO_2 fertilisation

7.2. Discussion

The obtained changes in irrigation water requirements are only partially explained by yield alterations - changes in soil moisture and CF-induced water efficiency gains are equally important and even have a larger effect in many regions. Therefore, the inclusion of water intensity as a parameter influenced by climate change is an important addition to the current assessments of climate change incidence through economic modelling, as most other modelling efforts have so far included changes in yields alone. Although crop water use in the model configuration employed in this chapter does not influence the model results, the changes in water productivity could be important in scenarios considering the economic impacts of water deficits. This type of analysis is conducted in the next chapter where water is considered as a distinct factor of production independent of irrigation equipment, and where the total regional water supply is restricted.

The analysis in this chapter addresses the uncertainty of climate change incidence over crop production with respect to climatic conditions through the use of multiple GCMs. This approach could be extended to crop performance uncertainty by using yield and irrigation water intensity data from alternative crop models. Although ISIMIP publishes results from other global models, there is a wide variation in the coverage of results in terms crop classes, CF variants and RCPs. Data from all other models, at the time of this analysis, does not cover all the relevant cases considered here. Considering the significant impact of CF on crop productivity, the inclusion of further crop modelling data incorporating insights from new field experiments would be welcome.

At the same time, the multi-model approach to cover the climate-crop-economic uncertainty dimensions undertaken in Nelson et al. (2014) but extended to include future water requirements would also require the comparison of the RESCU-Water model results with other global economic models. To the author's best knowledge, the expansion of irrigation as a function of market forces enabling regional changes to irrigation water requirements is possible only in a few water-focused models (PE IMPACT and MAgPIE; CGE in EPPA and BLS-AEZ). So far, only BLS-AEZ has been used to measure changes in irrigation water requirements, indicating that more economic modelling work would be needed in order to have a similar approach to that for land-use responses in Nelson et al. (2014) applied to blue water for crop production.

The changes in irrigation water demand obtained in this chapter differ from those in Fischer et al. (2007) where a significant increase in global requirements of about 11% is obtained for SRES A2r (RCP8.5 without CF). As discussed in section 7.2, the BLS water use response to climate change is however limited to soil moisture impacts and does not include the interactions between rainfed and irrigated production as a function of yield differentials.

Compared to the yield impacts implemented in Nelson et al. (2014), the incidence of climate change is considered in higher detail both through the inclusion of a larger number of crop types[35] and through the differentiated specification of rainfed and irrigated production. This

[35] Nelson et al. (2014) account for yield changes only for rice, maize, coarse grains and oil seeds.

wider coverage enables a more complete assessment of changes in crop output and prices, and the corresponding implications for food availability. The results in this chapter show a marked difference between the negative impacts over *wheat* and *rice* and the positive impacts over *cane&beet*, indicating significant alterations to the future crop production mix coming from changes in climatic conditions.

The adverse effects on crop output could be attenuated through several adaptation measures (Porter et al. 2014). One measure captured in the model simulations is the inter-crop substitution given relative yield changes. However, this leads to a possibly undesirable reduction in production of staple crops. Other crop management measures which are not considered but which could have a significant impact on yields include changes in sowing dates to cooler months[36] and the use of cultivars tolerant to high temperatures. However, at this stage, the implications of these solutions on water demand are not clear for extended geographical areas.

One limitation of the crop modelling data used is that the effects associated with CF strictly refer to current crop management conditions and are taken in isolation from the interactions with other GHG types. Therefore, the yield and water intensities values employed in the model scenarios do not embed the damaging effect of ozone over crop photosynthesis (see, for instance, McGrath et al. 2015). With the current emission patterns, the rise in CO_2 emissions will also be accompanied by increases in ozone precursor concentrations, leading to a non-linear impact of CF on crop performance (Porter et al. 2014). Yield could also be impacted by a likely decrease in herbicide effectiveness with the increase in CO_2 concentrations.

Another limitation applicable to both CF variants is that the impacts considered in the model simulations are a reflection of changes in conditions on the land areas currently harvested. With climate change, areas less used presently for crop production could become suitable in the future, leading to a positive impact on yields mainly in the high-latitude regions (IPCC 2014). This could further increase the differences in climate change incidence between temperate and tropical areas from those obtained in this chapter.

7.3. Conclusions

The analysis in this chapter determined the impacts of climate change on irrigation water requirements explained through changes in patterns of crop production and also through biophysical alterations to CWP (soil moisture and CF evapotranspiration changes). As already highlighted in the IPCC literature (Porter et al. 2014), higher CO_2 atmospheric concentrations

[36] By this, also enabling multiple cropping

determine very different impacts on crop production depending on whether CF is taken into account. The contrasts between the two CF variants and the variance between regions increases with CO_2 concentrations.

Changes in climatic conditions lead to an overall decrease in irrigation water productivity and crop output. The negative impacts are more pronounced for tropical than for temperate regions. Therefore, considering that the areas most affected are also those where most world population and economic growth will occur in the next decades, the adverse effects obtained raise food security concerns, in line with other climate change impact assessments. Adaptation to climate change mostly takes place through inter-crop substitution and less through additional irrigated production. The crop production mix could thus be altered towards more sugar output to the detriment of staple crops (*rice* and *wheat*) and *oil seeds*.

Without the CF effects, irrigation water requirements are reduced due to the overall lower crop yields leading to a significant drop in crop output. This decrease is partially offset by a reduction in water productivity in some regions where irrigated production is shifted towards crops that are more water-intensive. In other cases, mostly tropical regions, higher soil moisture coming from increases in precipitation is a driver for the further decrease in irrigation water demand. However, better soil water balances do not lead to more irrigated crop production as the yield reduction has a predominant effect.

A contrasting outcome is obtained when the CF effect is included in the model scenarios. Regional output generally increases across all crop classes, leading to a more balanced regional production of cereals, oils and sugars, whilst crop output and price impact disparities between regions also become narrower. Water requirements are considerably lower than in the baseline given the overall boost in water productivity induced by CF water efficiency gains. This reduction in water demand of crop production could free up important water resources for other uses throughout the economy.

Considering the significant impact of CF on crop output and water resources, more work is welcome in order to reduce the uncertainty of this dimension in the crop growing conditions. At the same time, a comparison of biophysical changes obtained through multiple crop models would be desirable for an increased diversity in modelling of yield responses and crop water efficiencies.

Chapter 8. Global economic impacts of regional water scarcity under different climate scenarios

8.1. Introduction

As most countries aspire to continued economic development, the evolution of water demand could sustain the upward trend in human withdrawals observed in the past century. So far, irrigation has been the most important driver in the expansion of global freshwater withdrawals. Nevertheless, other sectors have also played a significant role, notably in industrialised countries, e.g. water for power plant cooling in the US and Europe. The same tendency may occur in developing regions as their prosperity growth becomes more reliant on energy inputs and other water-intensive commodities in economic activities and final demand. Growth in population and urbanisation rates in these countries would also add an additional pressure on freshwater resources through higher municipal water demand by households. Global non-agricultural water uses are thus projected to expand fourfold for manufacturing and to more than double for thermal cooling and municipal uses (Marchal et al. 2011 p.216), with a higher expansion to occur notably in emerging economies.

With significant differences in the distribution of water endowments across world regions, the likely expansion in water demand in water-challenged areas will lead to generalised and more frequent imbalances between demand and supply. The water deficits could be persistent, and they already are in the many river basins that are currently being over-exploited. Furthermore, these imbalances could be exacerbated by climate variability and extreme weather events. The implications of disruptions to economic activities may be large-scale (WEF 2015) and could affect all sectors and households either directly through a reduction in water availability due to increased competition among users or indirectly through a reduction in the supply of water-intensive commodities. As markets become increasingly integrated internationally, the impacts could also be felt outside these regions.

There are now many studies projecting the size of future demand in the face of socioeconomic development (Shiklomanov & Balonishnikova 2003; Vorosmarty et al. 2000; Shen et al. 2008; Shen et al. 2014; Wada et al. 2016; Wada & Bierkens 2014; Hejazi et al. 2013). However, the measurement of the economy-wide impacts of water shortages stemming from the gap between a growing demand and a limited water supply is still at an incipient stage. Most economic modelling has been dedicated to the analysis of water scarcity in relation to crop production (Mark W. Rosegrant et al. 2002; Lotze-Campen et al. 2008; Calzadilla et al. 2010; Liu et al. 2016; Ponce et al. 2016; Winchester et al. 2016; OECD 2017). The underlying assumption in these studies is that non-crop users are not affected directly by water deficits. At the same time, economy-wide analyses of water scarcity (Darwin 2004; Berrittella et al. 2007) were either comparative-static or with limited elements in considering the relationship between socioeconomic development and water demand (see Table 3.2 in Chapter 3). Only the recent attempt discussed in Roson (2017) and disseminated in World Bank (2016) has tackled the link between socioeconomic development and water deficit, and the importance of water allocation across water users in conditions of constrained water use.

Climate change is a further complicating factor in understanding future demand patterns. Most water modelling efforts have embedded impacts of climate change on scarcity, however, in general, these have focused on the supply side through changes in run-off (Nelson et al. 2010; Calzadilla et al. 2013; Darwin 2004; Berrittella et al. 2007). On the demand side, this has been analysed only in relation to crop yields (Calzadilla et al. 2013; Ponce et al. 2016) – factor productivity shocks stemming from irrigated yield changes are applied to both irrigated land and irrigation equipment. As presented in Chapter 7, crop blue water productivity can also be influenced by other non-negligible factors such as natural soil moisture and changes in evapotranspiration rates specifically impacting irrigation water productivity.

This chapter aims to integrate within one economy-wide modelling framework both socioeconomic development and climate change as simultaneous determinants of demand-driven water deficits. The effects of population and economic growth on water demand are broken down by user type through distinct demand patterns. These water demand dynamics are partially explained internally (crops and livestock) and partially described outside the model by considering changes in structure, scale and efficiency in the use of water by economic activities (thermal power production, industrial and municipal water supply). The incidence of climate change is assessed for two carbon concentration pathways (RCP 2.6 and RCP 8.5) and refers only to changes in crop growing conditions without including the carbon fertilisation effect.

The unconstrained demand calculations based on the “middle of the road” SSP2 scenario are used to calibrate the RESCU-Water model for water scarcity simulations in the 2004-2050 horizon. Regions with excess water demand relative to a sustainable water supply threshold need to reduce this and implicitly re-allocate water across users according to alternative allocation methods. Given that water as an endowment is represented distinctly in the model, total supply can be distributed across users through scarcity price signals according to differences in water productivity. Water-abundant regions can also expand their water withdrawals to take advantage of their competitive advantage through international trade.

8.2. Establishing a global water demand baseline

8.2.1. Baseline calculation for 2004-2050

By using 2004 levels obtained through the water accounting work in Chapter 5 as base-year water uses, an unconstrained 'no scarcity' demand is projected across the five self-abstracting sectors – irrigated crops, livestock, thermal power production, industrial water supply and municipal water supply. This structure is similar to that found in the other studies focusing on the relationship between future freshwater demand and socioeconomic development (Flörke et al. 2013; Hanasaki et al. 2013; Wada & Bierkens 2014; Roson & Damania 2016).

Irrigation and livestock water demand

Water demand projections obtained endogenously are calculated through the use of a 'no scarcity' model baseline for the SSP2 pathway. As described in Chapter 6, socioeconomic development is integrated into RESCU-Water by taking into account exogenous GDP growth rates, changes in population, and changes in labour and capital supply. The 'no scarcity' world implies that any present or future water deficit does not have an impact on production and consumption decisions. In this run, instead of treating water endowments as a factor of production with a corresponding market price, water withdrawals are attached to the use of the irrigation facility as done in Chapters 6 and 7 for irrigation water, and directly to sectoral output for livestock.

The "bottom-up" representation of the crop sectors in the RESCU-Water framework facilitates the calculation of water demand for irrigation. Irrigation water requirements are thus determined by changes in crop demand coming from income and population growth. Patterns of irrigation water demand due to climate change are also taken into account using yield and irrigation water intensities data from crop modelling along the lines of Chapter 7.

Industrial and municipal water demand

Projections of industrial and municipal water use are undertaken outside the model framework and build on the work conducted previously in water scarcity assessment through biophysical modelling. The evolution of each of the two categories is thus determined separately and is explained by changes in scale, structure and efficiency in water use. The relationship between industrial water demand and economic activity is established similarly to the PCR-GLOBWB model (Wada et al. 2014) as a product of the scale of economic activity, economic development

(ED) and technological change (TC) (8.1). Industrial activity is calculated as the root square of changes in industrial gross value added (GVA^{ind}), specifying a slow-down in the expansion of industrial water demand with industrial output. Next, the ED component captures the changes in the structure of industrial activity as a function of per capita *GDP* and per capita energy demand *EN* (8.2). Last, the TC component reflects the tendency of technologies to become more water-efficient over time. In line with the approach in Wada et al. (2016), TC values distinguish between four types of regions depending on their hydrological and economic development profile. The GVA values used are determined by RESCU-Water through the 'no scarcity' baseline as an aggregated value for industrial sectors. The energy demand values are calculated through the TIAM-UCL model (Anandarajah et al. 2011) for SSP2 and are consistent with the power production projections used for the thermal cooling water calculations explained below.

$$IWD_t^r = IWD_{2004}^r * \frac{GVA_{r,t}^{ind}}{GVA_{r,2004}^{ind}}^{0.5} * ED_t^r * TC_t^r \qquad (8.1)$$

$$ED_t^r = AVERAGE\ (\frac{GDP_{r,t}^{pc}}{GDP_{r,2004}^{pc}}^{0.5}, \frac{EN_{r,t}^{pc}}{EN_{r,2004}^{pc}}^{0.5}) \qquad (8.2)$$

Municipal water demand (MWD) is determined similarly to industrial water (equation (8.3)). The MWD scale driver is the regional population, whilst changes in the structure of water use and water efficiency gains are captured through the same ED and TC parameters respectively, similarly to the industrial water demand.

$$MWD_t^r = MWD_{2004}^r * \frac{P_t}{P_{2004}} * ED_t^r * TC_t^r \qquad (8.3)$$

The values for water efficiency improvements through technological change are presented in Table 8.1. The industrial values are those used in the model inter-comparison work in Wada et al. (2016) for SSP2. The values for municipal water are lower than those for industrial water to mark a lower propensity of households and services to invest in water saving measures.

Table 8.1 - Technological change in industrial and municipal water use (annual efficiency improvement)

	HD	HI	LD	LI
Industrial	0.6%	1%	1%	1.1%
Municipal	0.3%	0.5%	0.5%	0.65%
Regions	China, Central Asia, Southeast Asia, North and South Latin America, Eurasia, Brazil, Central Africa, Sahel	Northern Europe, USA, Northeast Asia	India, South Asia, Northern Africa, Southern Africa	Middle East, Southern Europe, Australia&NZ

HD = water abundant developing, HI = water abundant industrialised, LD = water-scarce developing, LI = water scarce industrialised

Thermoelectric cooling water demand

The specification of water use for thermal power plant cooling is essential due to its weight in overall water abstraction, amounting to the combined volumes of the global industrial and municipal water uses. The dynamics in withdrawals for this use type are tied to electricity production coming from combustion plants. However, the relationship is not linear due to the changing nature of the thermoelectric generation mix and the large differences in water intensities between cooling technologies.

The baseline for cooling water demand is thus calculated bottom-up outside the RESCU-Water framework based on 'business-as-usual' electricity projections (no climate change policy) obtained from the TIAM-UCL energy systems model for SSP2. This calculation is completed in several steps (Figure 8.1) by taking into account changes both in the power production technological mix but also the possible evolution of cooling technologies towards more water-efficient options.

TIAM-UCL is a global linear optimisation model of the global energy system based on the TIMES modelling platform (Loulou & Labriet 2008). Energy production is determined for 16 world regions and is represented through a technology-rich bottom-up approach. The objective function of the partial equilibrium model is the minimisation of total discounted system costs at given exogenous production costs. The model is solved in 5-year time steps in the 2005-2100 time horizon and is primarily used to determine de-carbonisation pathways for different GHG concentration targets.

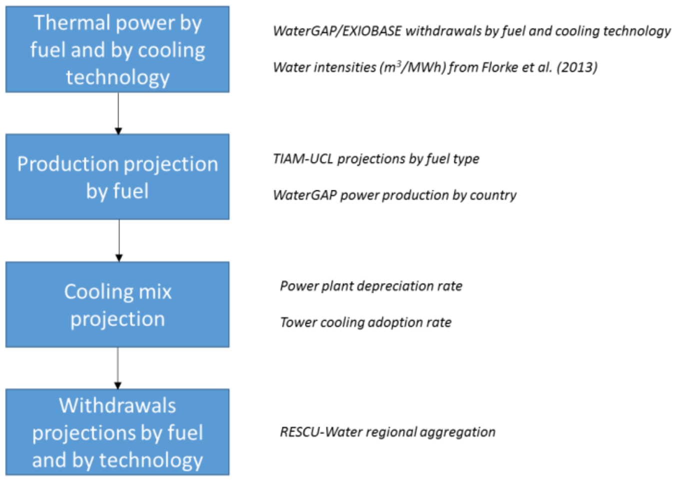

Figure 8.1 - Workflow for projecting thermal cooling water demand

In a first step, thermal power electricity generation by fuel and by cooling type is derived from the WaterGAP data published through EXIOBASE. The dataset comprises global water uses for 2007 reported across the two main cooling methods (once-through and tower cooling) and structured around 44 world regions. The relevance of the WaterGAP data consists of the selection of power plants based on their location such that only freshwater withdrawals for cooling are considered thus excluding coastline power generation. The translation of withdrawal values into electricity production value is done using the water intensities measured in m^3/MWh (Table 8.2) employed initially in Flörke et al. (2013) to determine thermal cooling withdrawals.

Table 8.2 - Power plant water intensities by cooling method (m^3/MWh)

Fuel	**Once-through**	**Tower (closed-loop)**
Coal	132.5	2.1
Nuclear	160.85	1.5
Gas (combined cycle)	52.05	0.4

Data source: Flörke et al. (2013)

In the second step, EXIOBASE/WaterGAP regional production values are downscaled to a country level by using disaggregated production information[37] for the base year. Production by fuel type is then projected using growth rates[38] obtained from TIAM-UCL for a business-as-usual climate policy assumption using SSP2 GDP and population dynamics. As the regional aggregation in TIAM-UCL is different from that in EXIOBASE, each country inherits the production dynamics of its TIAM region and the initial regional cooling mix of its EXIOBASE region.

The cooling mix evolution is then determined in the third step. This calculation is done by taking into account that newer power plants are likely to become more water-efficient through a gradual adoption of tower-cooling. For each year, power generation by fuel and by cooling type is split into two vintages. The "old" vintage represents the production capacity inherited from the previous year depreciated with a 2.5% rate (40-year lifetime assumption for power plants) and for which the cooling mix is fixed. The "new" vintage is the additional capacity required to generate electricity up to the annual projected levels. The new vintage uses a *tower/once-through cooling ratio* updated annually in which the weight of tower cooling progresses by 2%.

In the fourth step, production values by fuel and by cooling method combined with the water intensities in Table 8.2 enable the calculation of withdrawals along the two dimensions in the 2004-2050 time horizon. Withdrawals are thus affected both by changes in production

[37] Country-level electricity generation values were obtained from Dr. Martina Flörke through personal communication
[38] Negative growth rates are used to calculate pre-2007 production values

technologies with some fuels being more efficient than others (e.g. gas versus coal) and by changes in the cooling mix with a tendency towards the use of more water-efficient methods. Finally, as the RESCU-Water model combines all thermal production technologies into one sector, all country-level cooling withdrawals are summed up and aggregated to the RESCU-Water regional structure.

8.2.2. Global withdrawals

In the RESCU-Water baseline, global withdrawals in 2050 grow by 55% compared to the base year 2004 to reach 5 539km^3. As obtained previously for SSP2, irrigation water demand grows by only 9%, whereas other uses have a more pronounced expansion – industrial (436%), municipal (249%), thermal cooling (67%), livestock (37%).

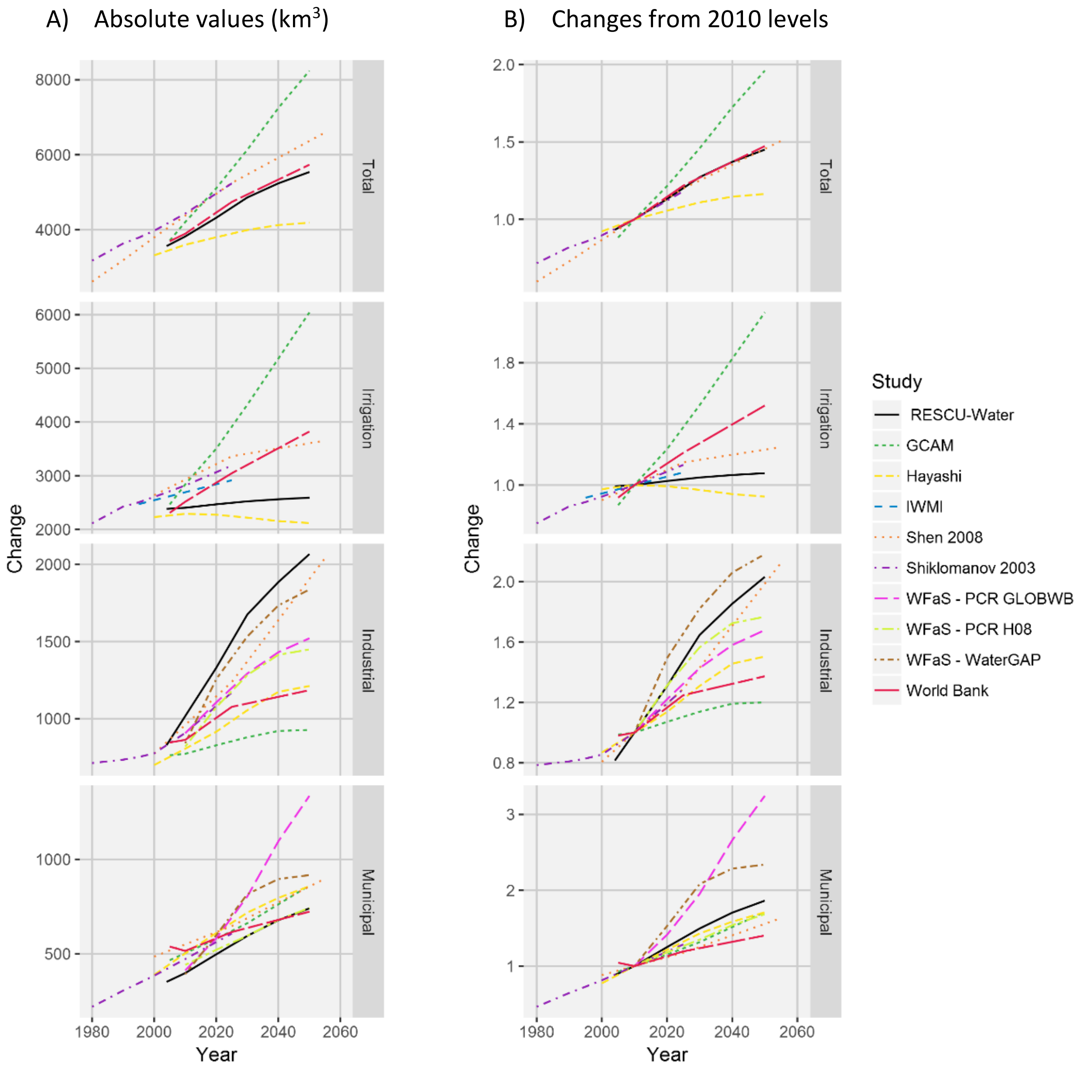

Figure 8.2 - Baseline withdrawals compared to other studies

Studies: RESCU-Water (this chapter), GCAM (Hejazi et al. 2014), Hayashi (Hayashi et al. 2013), IWMI (de Fraiture et al. 2010), Shen 2008 (Shen et al. 2008), Shiklomanov 2003 (Shiklomanov & Balonishnikova 2003), WFaS PCR GLOBWB, H08, WaterGAP in (Wada et al. 2016), World Bank (World Bank 2016)

These RESCU-Water total withdrawal values are comparable to other global projections. Figure 8.2A shows the global withdrawals expressed in absolute terms obtained across a number of modelling efforts. As base years and withdrawal reference values differ from one study to another, to capture the scale in the expansion of water demand, relative changes[39] are also included in Figure 8.2B. It should be noted, that the structure of withdrawals varies across studies, whilst only a subset of the projections covers all water withdrawals, with some focusing on specific user categories, e.g. industrial and municipal water in Wada et al. (2016).

Irrigation withdrawals for the RESCU-Water baseline are found at the lower end of projections. Industrial withdrawals (reported in Figure 8.2B as the sum of industrial supply and thermal cooling for comparative reasons[40]) are on the higher end of the projected values. Interestingly, the lowest growth and the highest growth of industrial water demand are obtained in GCAM and WaterGAP which both separate manufacturing and thermal cooling withdrawal dynamics, with changes for RESCU-Water being more in line with those obtained in WaterGAP. For municipal water demand, the baseline values are similar to the more central estimates.

8.2.3. Regional withdrawals

Regions expanding most their total water demand are those with a high increase in GDP and population. Therefore, baseline withdrawals for 2004-2050 see a considerable growth in most developing regions. Also, as demand in non-agricultural uses expands at high rates, irrigation withdrawals generally fall in importance, although maintaining a dominant role in most cases – see Figure 8.3.

Total water demand in China is largely driven by a ten-fold increase in industrial water requirements from 2004 levels and a doubling of municipal and thermal cooling water demands. Central Africa has a more balanced growth with municipal and industrial demand playing equal parts. Thermal cooling demand doubles; however, it remains at insignificant levels in the region. Demand in Brazil is also determined by an important growth across all non-agricultural users.

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[39] The year 2010 was chosen as reference to allow comparison with the WFaS work in Wada et al. (2016) which only report data starting with this year

[40] Only GCAM reports projections for thermal cooling withdrawals; WaterGAP values for thermal and manufacturing withdrawals are bundled as industrial uses in Wada et al. (2016)

Figure 8.3 - Regional withdrawals 2004 and 2050 by use category (in km^3)

For the industrialised regions, the sign of change varies from one case to another. The USA sees an expansion of withdrawals by 17% mainly driven by municipal withdrawals. Australia&NZ face a similar dynamic leading to an increase of 27% in total withdrawals. The expansion in cooling water determines a significant growth in total demand in Northern Europe, as the TIAM-UCL 'business-as-usual' scenario for power production relies largely on thermoelectric generation. In contrast, the reduction in withdrawals in Canada is driven by a decrease in thermal cooling withdrawals.

The baseline water demand indicates that regions which are already water-stressed continue to increase their reliance on unsustainable water withdrawals. Regions with base year withdrawal levels close to or even above the TRWR (Middle East and South Asia) further expand the pressure over their aquifers - Table 8.3. Northern Africa is also approaching the upper limit of renewable water availability by 2050.

Table 8.3 - Regional withdrawals in 2004 and 2050 relative to TRWR

RESCU-Water region	**Total withdrawals (km³)**		**Change**	**% TRWR**	
	2004	**2050**		**2004**	**2050**
India	662.9	1,050.8	59%	35.0%	55.4%
China	511.5	985.3	93%	17.7%	34.0%
USA	451.6	526.8	17%	21.6%	25.2%
Middle East	402.3	569.8	42%	97.6%	138.2%
South Asia	316.2	331.8	5%	109.0%	114.4%
Southeast Asia	276.2	395.6	43%	4.1%	5.8%
Northern Africa	172.2	201.9	17%	79.6%	93.3%
Southern Europe	158.8	166.3	5%	17.1%	17.9%
North Latin Am	137.6	247.9	80%	7.4%	13.2%
Central Asia	88.9	143.7	62%	20.1%	32.4%
Northern Europe	88.0	186.7	112%	6.8%	14.4%
Eurasia	79.7	181.8	128%	1.7%	3.9%
Northeast Asia	56.2	52.9	-6%	10.0%	9.4%
Canada	40.3	26.3	-35%	1.4%	0.9%
South Latin Am	37.4	105.8	183%	2.0%	5.7%
Brazil	27.8	51.5	85%	0.3%	0.6%
Australia &NZ	25.8	32.8	27%	3.2%	4.0%
Central Africa	23.7	49.9	110%	0.9%	1.9%
Southern Africa	17.6	25.2	43%	8.6%	12.3%
Sahel	9.3	13.6	47%	0.9%	1.3%

The results obtained for each RESCU-Water region cannot be thoroughly compared to other studies. Other projections are generally reported as global aggregates, with only the WFaS model inter-comparison work in Wada et al. (2016) presenting results for a sample of eight countries of which only four are distinctly accounted for in RESCU-Water. In the 2010-2050 period, industrial withdrawals for China[41] grow five times in WaterGAP and six times in PCR-GLOBWB, whereas H08 reports an increase of only 30% and also projects a decline post-2030. The corresponding values in RESCU-Water lead to a sixfold increase, comparable thus to PCR-GLOBWB. For municipal water, the expansion patterns across the three WFaS models are similar to that of industrial uses. Hence RESCU-Water values are lower than WaterGAP and PCR-GLOBWB but higher than H08. The agreement of the RESCU baseline with the WFaS models output is lower for the industrialised regions. WaterGAP and H08 report a marked decrease in the USA for industrial water demand, whilst the RESCU-Water projections increase slightly by 5%. The USA municipal water demand increases significantly in H08 and PCR-GLOBWB, similarly to RESCU-Water, but less so in WaterGAP.

8.2.4. Thermal cooling withdrawals

Thermoelectric production using freshwater for cooling purposes grows across all regions except Canada. Globally production grows by 141% in the 2004-2050 period with the highest increases occurring in China, Northern Europe, India, USA and Eurasia (Figure 8.4B). Global freshwater withdrawals required for these production levels increase by only 67% due to the transition towards a more water-efficient cooling methods mix.

Tower cooling thus expands withdrawals by 182% compared to 64% for once-through. Nevertheless, given the significant difference in water withdrawal intensities between the two cooling methods, freshwater volumes for once-through cooling are still dominant (Figure 8.4C) despite the growth in electricity output coming mainly from tower-cooled power plants (Figure 8.4D).

8.3. Economic modelling of demand-driven water scarcity

The baseline demand values per user category are used to calibrate the RESCU-Water model for further scenario analysis (Figure 8.5). The regional baseline withdrawals are then employed for the identification of regions which are exceeding the freshwater sustainable supply levels. The impacts of the resulting regional water deficits over economic activity, welfare and food security are determined through RESCU-Water by using four alternative allocation methods as described below.

[41] Again, industrial withdrawals in Wada et al. (2016) include thermal cooling values. The comparison with RESCU-Water is made accordingly.

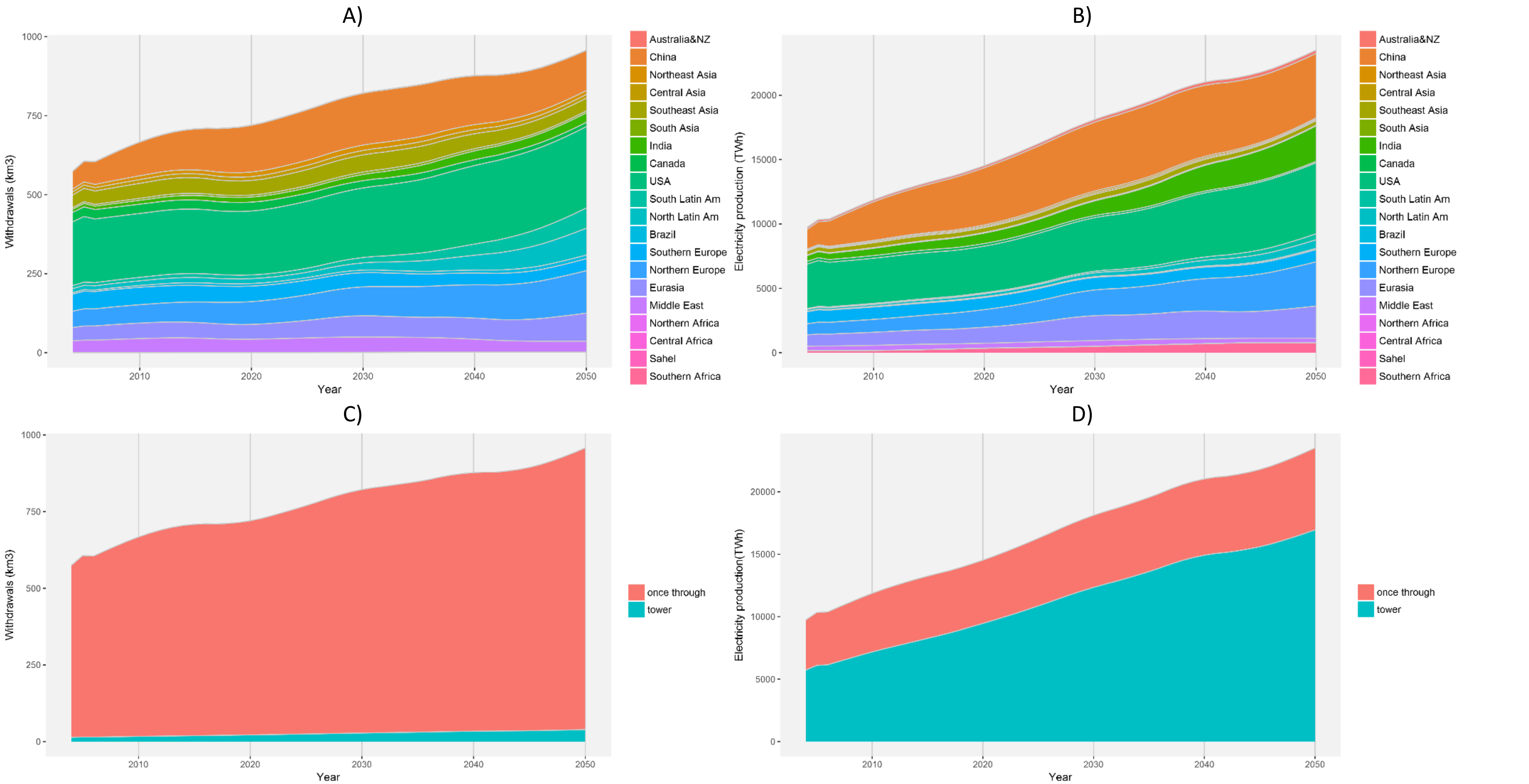

Figure 8.4 – Thermal power withdrawals and electricity production by region and by cooling method – 2004-2050

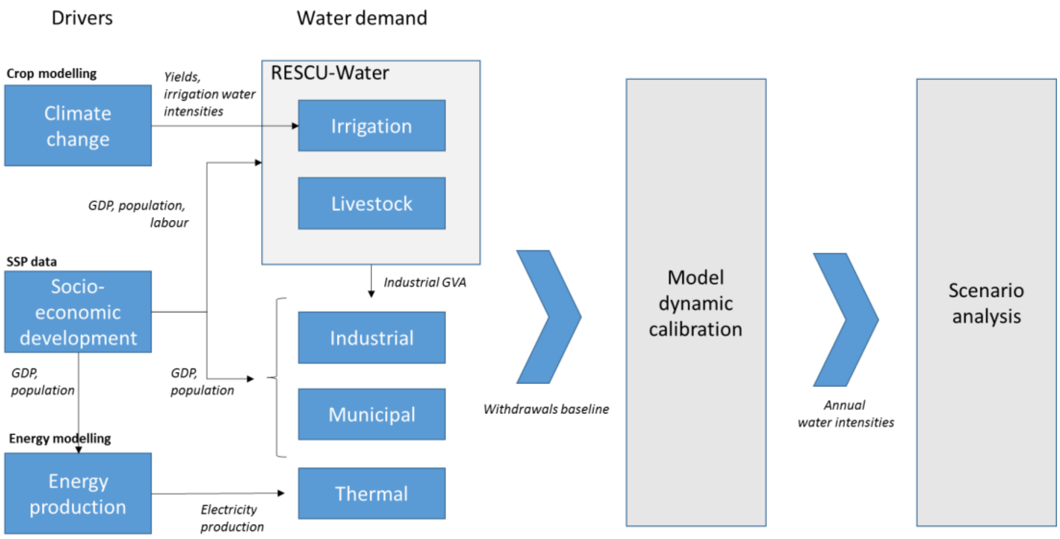

Figure 8.5 - Baseline withdrawals integration in RESCU-Water simulations

8.3.1. Model dynamic calibration

The RESCU-Water model is calibrated across the 2004-2050 time frame to reproduce withdrawal levels under a 'no scarcity' pathway in line with the baseline projections across the five classes of self-abstracting activities calculated previously. Considering that the model already determines water withdrawals for irrigation and livestock endogenously, the calibration is required only for the other three sectors – thermal electricity *elt*, industrial water supply *iwt* and municipal water supply *mwt*.

As described in Chapter 4 section 4.4.2.1, the nesting of inputs in the production functions of these sectors is similar. Therefore, the calibration is conducted in the same way for both and is done by using equation (8.4). The equation adjusts the annual levels of the water productivity factor $\phi_{Water,sai,t}$ associated to the water factor inputs in the top-level Leontief nest of the production tree (see equation (4.16) in Chapter 4).

$$\phi_{Water,sai,t} = \alpha_{Water}^{sai} \frac{XP_{sai,t}}{W_{sai,t}} \tag{8.4}$$

$$\alpha_{Water}^{sai} = \frac{W_{sai,2004}}{XP_{sai,2004}} \tag{8.5}$$

$XP_{sai,t}$ is the sectoral output determined in the model 'no scarcity' baseline where water is not included as a distinct factor of production and in which the constraints of water scarcity are not considered. $W_{sai,t}$ represents the sectoral water withdrawals values as determined in the water demand baseline described above. The α_{Water}^{sai} is the water share parameter as calculated through the base year model calibration with the $\phi_{Water,sai,t}$ factor productivity equal to 1 (equation (8.5)).

8.3.2. Water scarcity analysis under different allocation regimes

The modelling of water scarcity implies a reduction in water availability for economic activities in regions which currently are exceeding or are projected to exceed the levels of long-term sustainable water withdrawals. The introduction of scarcity is thus done by scaling down the water supply FS_{water} in these regions from the unconstrained total demand levels down to a region-specific sustainable withdrawals threshold SWT_r. This supply constraint implies the occurrence of scarcity rents which guide the way freshwater resources are allocated throughout the economy.

The effective introduction of water as a distinct factor of production is done only in water-scarce regions. For these cases, water demand by self-abstracting sectors is endogenised through a specific model variable $XF_{Water,sai}$ (see equation 4.16 in Chapter 4). For the 'no scarcity' model base case, total supply of water FS_{water} in each year t is specified to match the sum of all unconstrained demand levels $W_{sai,t}$. Therefore, with the calibrated $\phi_{Water,sai,t}$ values, the model generates sectoral demands $XF_{Water,sai}$ equal to $W_{sai,t}$ and which sum up to the exogenously specified total supply FS_{water} at a water market price of zero i.e. no scarcity rents.

In the other regions, water use calculations are exogenous to the model and are done by multiplying the sectoral output $XP_{sai,t}$ with the α_{Water}^{sai} parameter adjusted for water productivity changes $\phi_{Water,sai,t}$. Through this specification, water inputs are not introduced as independent model variables and thus are not a determinant in production choices, allowing water use to expand or contract given the impacts transmitted from water scarce regions.

By assuming a perfect mobility of water, the water allocation is done such that the marginal productivity across sectors is equal and that the shadow value of water is equal to the observable scarcity rents. Nevertheless, it is acknowledged that perfect mobility is difficult to obtain as this would imply the existence of economy-wide water markets, and that of intra- and inter-basin routing infrastructure. Therefore, the model allows alternative assumptions for water mobility through the introduction of different allocation methods:

1. Full allocation (FA) – the existence of one single water market within a region in which all water resources are tradeable between any given self-abstracting sectors.
2. Limited mobility (LM) - only a fraction of 5% can be re-allocated across users based on scarcity price information.
3. Fragmented markets (FM) – water use for crops and non-crop sectors is completely separated, and the reduction in water availability for each is proportional to the overall reduction in unconstrained withdrawals.

4. Agriculture-last (AL) – only the use of irrigation water is constrained whilst non-crop users are free-riders.

The first method (FA) implies that one single water market price applies to all users. Although examples of economy-wide trading of water rights do not currently exist, this method serves as a benchmark for water allocative efficiency. The second method (LM) assumes a reduced degree of mobility of water resources across the wider economic sectors. The assumption behind this market arrangement is that some limited trade-offs can occur between large water users enabling high-value activities to compensate for low-value activities for freeing up water resources. For instance, municipal water supply could expand water withdrawals by paying larger irrigation schemes for curtailing their unconstrained demand. The third method implies an allocation by separating water allocative efficiency across crop types from that across non-crop sectors. This method is also used in Berrittella et al. (2007a). The fourth method is that found in most water scarcity modelling and uses the assumption that agriculture is the user with the lowest priority. Water availability for irrigation is thus determined once all other unconstrained water uses have been deducted from the total sustainable supply. Water resources can still be mobile but only between different crop classes.

Whilst the implementation of the first allocation method is inherent to the model specification described in Chapter 4, the modelling of the next three methods requires changing the water demand functions of the self-abstracting sectors. For the second method, only a part of the water resources is re-allocable. In the model, this re-allocation is achieved through the introduction of a fraction of resources that is allocated at no cost and in fixed volumes to the different economic activities. Each sector is thus entitled to a $FREE\_WATER^r_{sai,t}$ volume calculated for each simulation year t (equation (8.6)) as a share $free\_alloc$ applied to the unconstrained water demand $W^r_{sai,t}$ adjusted by a water demand reduction rate wdr^r_t. The reduction rate wdr^r_t represents the change in total regional water demand required to cap withdrawals at a regional sustainable threshold SWT_r and is calculated annually to reflect changes in the 'no scarcity' baseline withdrawals due to socioeconomic development (equation (8.7)).

$$FREE\_WATER^r_{sai,t} \;=\; wdr^r_t * W^r_{sai,t} * free\_alloc \tag{8.6}$$

$$wdr^r_t = \frac{SWT_r}{\sum_{sai} W^r_{sai,t}} \tag{8.7}$$

The difference $1\text{-}free\_alloc$ represents the fraction of water resources which can be re-allocated between sectors. Each sector is thus using all its free water as this volume is not influenced by the scarcity price signals, and then adjusts any additional water demand based on its relative water productivity. The cost functions of non-crop self-abstracting industries are modified to account for the partial free allocation of water (equation (8.8)) by factoring in a water cost share wcs_{sai} reflecting the share of water demand for which the water price PF_{Water} applies (equation (8.10)). For irrigated crops, the cost function for the land bundle in equation (4.11) from Chapter 4 is altered through equation (8.9). Due to the market clearing condition, the sum of demand by all users is equal to the regional water supply $FS_{Water,r}$ set at the sustainable withdrawals thresholds SWT_r (equation (8.11)).

$$PX_{sai} = \alpha_{VA}^{sai}\, PVA_{sai} + \alpha_{ND}^{sai}\, PND_{sai} + \frac{\alpha_{Water}^{sai} wcs_{sai} PF_{Water}}{\phi_{Water,sai}} \tag{8.8}$$

$$PLND_{irc} = \alpha_{IrrLand}^{LND}\, \frac{\left(1+\tau_{IrrLand}^{F}\right) PF_{IrrLand}}{\theta_{IrrLand}^{LND}} + \alpha_{Irrigation}^{LND}\, \frac{\left(1+\tau_{Irrigation}^{F}\right) PF_{Irrigation}}{\theta_{Irrigation}^{LND}} + \alpha_{Water}^{LND}\, \frac{wcs_{irc} PF_{Irrigation}}{\theta_{Water}^{LND}} \tag{8.9}$$

$$wcs_{sai} = \frac{\left(XF_{Water,sai} - FREE\_WATER_{sai}\right)}{XF_{Water,sai}} \tag{8.10}$$

$$FS_{Water,r} = SWT_r \tag{8.11}$$

The free allocation fraction $free\_alloc$ is set to 0.95 implying that almost all resources are allocated at no cost. This determines only the remaining 5% of the sustainable water supply to be shifted from one activity to another and results in a reduction of all water uses almost proportional to that of total water withdrawals.

In the third allocation method, the exogenous supply of water is separated into two independent supply variables – *FSWA* for crops and *FSWI* for non-crops. The market clearing condition for water endowments (equation 4.65) is thus specified distinctly for the two supply types (equations (8.12) and (8.13)).The exogenous levels of *FSWA* and *FSWI* are set such that the reduction from unconstrained withdrawals for each of two water user groups is proportional to the overall required reduction to meet the regional sustainability threshold.

$$FSWA_r = \sum_{crops} XF_{Water,crops,r} \tag{8.12}$$

$$FSWI_r = \sum_{non-crops} XF_{Water,non-crops,r} \tag{8.13}$$

The fourth allocation method (AL) is enabled by specifying water as a production factor only to irrigated crops. The use of water by non-crop self-abstracting sectors $EXF_{Water,sai}$ is proportional to the output of these sectors by using the sector specific water intensities and the calibrated water productivities $\phi_{Water,sai,t}$ (equation (8.14)). Thus, scarcity rents PF_{Water} are not included in the cost function of these sectors and therefore do not influence water demand in these activities. To determine water availability for irrigation, the $EXF_{Water,sai}$ volumes are deducted from the sustainable thresholds SWT_r (equation (8.15)) to determine total water supply applicable only to irrigated crops (equation (8.16)).

$$EXF_{Water,sai} = \frac{\alpha_{Water}^{sai} XP_{sai}}{\phi_{Water,sai}} \tag{8.14}$$

$$FS_{Water,r} = SWT_r - \sum_{sai} EXF_{Water,sai,r} \tag{8.15}$$

$$FS_{Water,r} = \sum_{irc} XF_{Water,irc,r} \tag{8.16}$$

8.3.3. Sustainable withdrawals thresholds

Thresholds for sustainable withdrawals are set for regions which are already either using a large share of their renewable resources or are experiencing recurring groundwater depletion. Middle East, Northern Africa and South Asia qualify through both criteria, whereas India experiences river basin overexploitation in many areas (Wada et al. 2010; Rodell et al. 2009).

In light of this regional heterogeneity, a few sustainability thresholds can be considered – TRWR; TRWR with environmental flows requirements deducted; or 40% of TRWR as a marker for severe water stress following the thresholds in Alcamo et al. (2003). The first is an absolute withdrawal limit given by renewable water availability measured through TRWR. Regions going over this value are certain to have a generalised aquifer over-exploitation. The second standard includes the environmental flow requirements which in Figure 8.6 are considered to be 20% of TRWR as the lower bound for the estimations in Smakhtin et al. (2004). The third threshold also accounts for the intra-annual accessibility of freshwater resources and the risk of impairment of environmental requirements and downstream users within a river basin.

For each region a different sustainability level is set – India 40% of TRWR to prevent a significant further amplification of groundwater depletion[42], South Asia and Northern Africa 80% of TRWR (TRWR minus EFR), Middle East 100% of TRWR. The choice of 100% TRWR threshold for the Middle East comes from the infeasibility in finding a model solution with 80% threshold in the agriculture-last (AL) allocation method – the implied reduction in water availability for irrigated crops (234km^3) in 2050 almost matches the overall baseline demand for irrigation (263km^3). Withdrawals in India are capped starting from 2015. South Asia is above the 80% standard already in the base year. Therefore withdrawals are gradually decreased down to meet this level

[42] This threshold, being higher than 2004 levels, also assumes that withdrawals can be expanded in river basins which are not currently over-exploited.

by 2050. Withdrawals in Northern Africa are capped starting with 2005. The Middle East gradually decreases to 100% by 2050. At the end of the simulation period, the absolute reduction from unconstrained levels is 247km^3 for India, 108 km^3 for South Asia, 151 km^3 for the Middle East and 16 km^3 for Northern Africa.

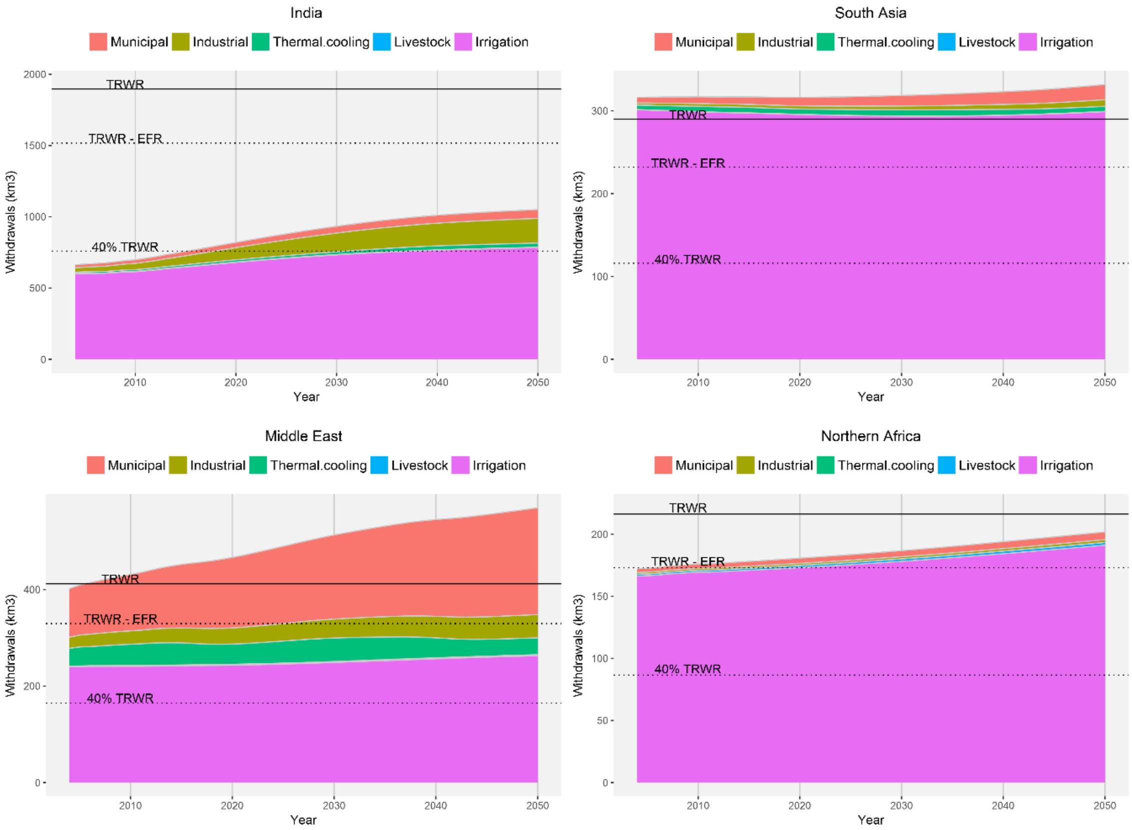

Figure 8.6 - Baseline withdrawals in regions with water deficits – 2004-2050

8.3.4. Demand-driven water scarcity scenarios

The impacts of water scarcity are assessed through two main scenarios (Table 8.4). The first refers to socioeconomic development under 'middle-of-the-road' SSP2 without considering the effects of climate changes. In this 'no climate change' case, the RESCU-Water model calibrated to reproduce the unconstrained water demand from the baseline calculations is constrained to cap withdrawals to a regional sustainable threshold. The four allocation methods (FA, LM, MF, AL) introduced in Section 8.3.2 are used to compare impacts regarding changes in GDP, sectoral output, trade and welfare (Equivalent Variation) according to the different allocation principles. Food security impacts are also taken into account by analysing changes in crop production and crop prices.

For the second scenario, water demand intensities in irrigated crop production are altered to account for changes in crop growing conditions across two climate change pathways – RCP 2.6 and RCP 8.5. As opposed to Chapters 6 and 7, the model configuration includes water as a distinct factor of production. Therefore, the climate change impacts considered (changes in yields and soil moisture) imply modifying the factor productivities θ_{Water}^{LND} associated with water inputs into irrigated crops. Due to the significant uncertainties and to simplify the assessment, CO_2 fertilisation effects over crop water productivity are not included, although these can be an important source of water use savings in irrigation as explored in the previous chapter. To test the dependency of climate change impacts on water management policies, two allocation methods are used (FA and AL).

Table 8.4 - Water scarcity simulations

Main scenario	RCP	SSP	Climate change incidence	GCM*	Allocation methods
No climate change	n/a	SSP2	n/a	n/a	FA, LM, MF, AL
With climate change	RCP 2.6 RCP 8.5	SSP2	Yield, evapo-transpiration, natural soil moisture	HADGEM2 IPSL MIROC	FA, AL

Note: (*) similarly to Chapter 7, the model simulations include climate change impacts for each GCM separately, however, results are presented by RCP and as averages across the three alternative climate responses.

8.4. Results

8.4.1. No climate change scenario results

8.4.1.1. Economic output impacts

The economic impacts of water scarcity are felt at an aggregate level mostly in water-scarce regions (Table 8.5), with only minor influences for the other regions. Nevertheless, by 2050, the negative impacts over world GDP measured in real terms could be in the order of 0.15%, or over \$130bn GDP losses under the more inflexible water allocation regimes (limited mobility *LM* and market fragmentation *MF*). The impacts are reduced by two-thirds under the assumption of economy-wide water trading (the *FA* water market configuration) and are further reduced to negligible levels under the agriculture last *AL* regime. This finding is an indication that greater GDP impacts are obtained with increased constraints on the water availability to non-agricultural sectors.

Compared to the GDP reductions, the welfare impacts of water deficits are considerably lower in water-scarce regions in the LM, FA and MF cases. Depending on the incidence of scarcity on the different economic sectors, some consumer prices can decrease leading even to positive EV outcomes (India – MF, South Asia – AL). In the other regions, the impacts turn from positive GDP to negative EV as domestic prices of demand commodities increase due to the expansion of foreign demand.

Table 8.5 - Real GDP and Equivalent Variation impacts by RESCU-Water region in 2050 relative to the baseline

RESCU-Water region	LM			AL			FA			MF		
	% RGDP	$bn RGDP	$bn EV	% RGDP	$bn RGDP	$bn EV	% RGDP	$bn RGDP	$bn EV	% RGDP	$bn RGDP	$bn EV
Middle East	*(1.797)*	(89.04)	(10.76)	*(0.020)*	(0.97)	(3.07)	*(0.761)*	(37.71)	(9.71)	*(1.841)*	(91.22)	(15.69)
South Asia	*(1.606)*	(7.07)	(1.51)	*(0.562)*	(2.47)	0.13	*(0.530)*	(2.33)	(0.10)	*(0.554)*	(2.44)	(0.63)
India	*(0.435)*	(33.19)	(7.80)	*(0.029)*	(2.24)	(3.53)	*(0.148)*	(11.26)	(0.96)	*(0.465)*	(35.43)	5.11
Northern Africa	*(0.022)*	(0.29)	(0.63)	*(0.003)*	(0.04)	(0.05)	*(0.012)*	(0.16)	(0.01)	*(0.010)*	(0.14)	(0.44)
Central Asia	*(0.016)*	(0.04)	0.00	*(0.001)*	(0.00)	(0.03)	*(0.003)*	(0.01)	(0.02)	*(0.006)*	(0.01)	(0.05)
Eurasia	*(0.009)*	(0.12)	0.05	*(0.000)*	(0.00)	(0.02)	*(0.002)*	(0.03)	(0.02)	*(0.006)*	(0.07)	(0.10)
China	*(0.002)*	(0.30)	(0.51)	*0.000*	0.05	(0.16)	*(0.001)*	(0.11)	(0.28)	*(0.004)*	(0.50)	(0.62)
Southeast Asia	*(0.002)*	(0.06)	(0.58)	*0.003*	0.10	(0.28)	*0.000*	0.00	(0.36)	*(0.005)*	(0.16)	(0.61)
Northern Europe	*(0.002)*	(0.19)	0.33	*0.000*	0.05	(0.05)	*(0.000)*	(0.03)	(0.09)	*(0.002)*	(0.23)	0.06
Southern Europe	*(0.001)*	(0.05)	(0.12)	*0.001*	0.08	(0.29)	*(0.000)*	(0.01)	(0.15)	*(0.002)*	(0.18)	(0.12)
Northeast Asia	*(0.000)*	(0.00)	0.07	*0.002*	0.09	0.05	*0.000*	0.02	(0.02)	*(0.002)*	(0.09)	(0.11)
USA	*0.000*	0.04	(1.19)	*0.001*	0.25	(2.69)	*0.001*	0.11	(1.69)	*(0.000)*	(0.03)	(1.74)
Sahel	*0.001*	0.00	(0.04)	*0.000*	0.00	(0.02)	*(0.001)*	(0.00)	(0.03)	*0.002*	0.00	(0.06)
Canada	*0.000*	0.01	(0.08)	*0.001*	0.02	(0.08)	*0.001*	0.01	(0.10)	*0.001*	0.02	(0.19)
North Latin Am	*(0.001)*	(0.04)	(0.21)	*0.001*	0.03	(0.11)	*0.001*	0.04	(0.23)	*0.002*	0.10	(0.55)
Australia&NZ	*0.001*	0.01	(0.01)	*0.003*	0.06	(0.12)	*0.002*	0.03	(0.10)	*(0.000)*	(0.01)	(0.07)
Southern Africa	*0.001*	0.01	(0.09)	*0.008*	0.07	(0.05)	*0.003*	0.03	(0.05)	*(0.003)*	(0.02)	(0.07)
Brazil	*0.002*	0.02	(0.28)	*0.005*	0.05	(0.47)	*0.003*	0.03	(0.32)	*0.001*	0.01	(0.30)
South Latin Am	*0.005*	0.03	(0.13)	*0.008*	0.04	(0.23)	*0.004*	0.02	(0.14)	*0.002*	0.01	(0.10)
Central Africa	*(0.006)*	(0.09)	(0.34)	*0.016*	0.25	(0.48)	*0.012*	0.18	(0.54)	*0.009*	0.14	(0.79)
World	***(0.146)***	(130.36)	(23.84)	***(0.005)***	(4.60)	(11.57)	***(0.057)***	(51.18)	(14.92)	***(0.146)***	(130.26)	(17.07)

In water-scarce regions, the incidence of the allocation regimes is dependent on the regional unconstrained water demand patterns in the baseline. The highest impacts in all four regions are obtained in the LM variant (Figure 8.7), with the highest impacts in the Middle East and South Asia. The MF variant produces similar results to LM in India and the Middle East; as opposed to the other two regions, non-irrigation water demand consistently increases its weight in overall withdrawals by 2050, and therefore the requirement for more flexibility in water re-allocation away from irrigation becomes more stringent. The AL method, affecting mostly crop production, leads to low GDP impacts except for South Asia where food sectors continue to have an important weight in the economy. Northern Africa is generally unaffected by water scarcity given the dominant role of irrigation in overall withdrawals persisting in 2050 - small volumes of water re-allocation even within the mobility limits of the LM case (5% of total supply) are sufficient to ensure the resilience to water shortages of the economy as a whole. Therefore, there are important differences in the incidence of water scarcity between the first three (India, South Asia and Middle East) and this region.

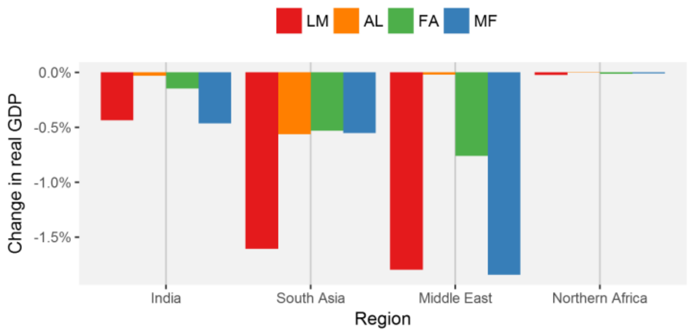

Figure 8.7 - Real GDP impacts by region and by allocation method in 2050 relative to the baseline

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At a sectoral level, water scarcity impacts the activities with the highest dependency on water inputs given their substitution possibilities away from water use (Figure 8.8). Thus, crop production sees a drop of 5% or more in output in India, South Asia and the Middle East with cascading effects over the processed food sector. As explored below, irrigated crop production drops by even higher rates with increases in rainfed production only partially offsetting this effect. The same applies to the power generation sector – thermal electricity has the highest reduction in output of all activities, with the production mix switching towards non-thermal power.

Industrial sectors with inflexible production functions with regard to industrial water use (chemicals, primary energy, mining, manufacturing, paper and construction) are also affected but to a lower degree. The typical drop in output for these sectors for the LM method is 2% in the Middle East, 1% in India and 3.5% in South Asia. In the other water allocation methods, the output reduction is lower although still significant for the MF method, negligible for FA and even positive in some cases for AL. In Northern Africa, although the impacts of the different allocation regimes are generally negligible, industrial output increases in the LM case with more mixed outcomes for the other methods. In the LM regime, the limited flexibility to optimise water allocation within crop production across the different crop types determines an overall crop output reduction with a re-allocation of water resources to the non-crop sectors.

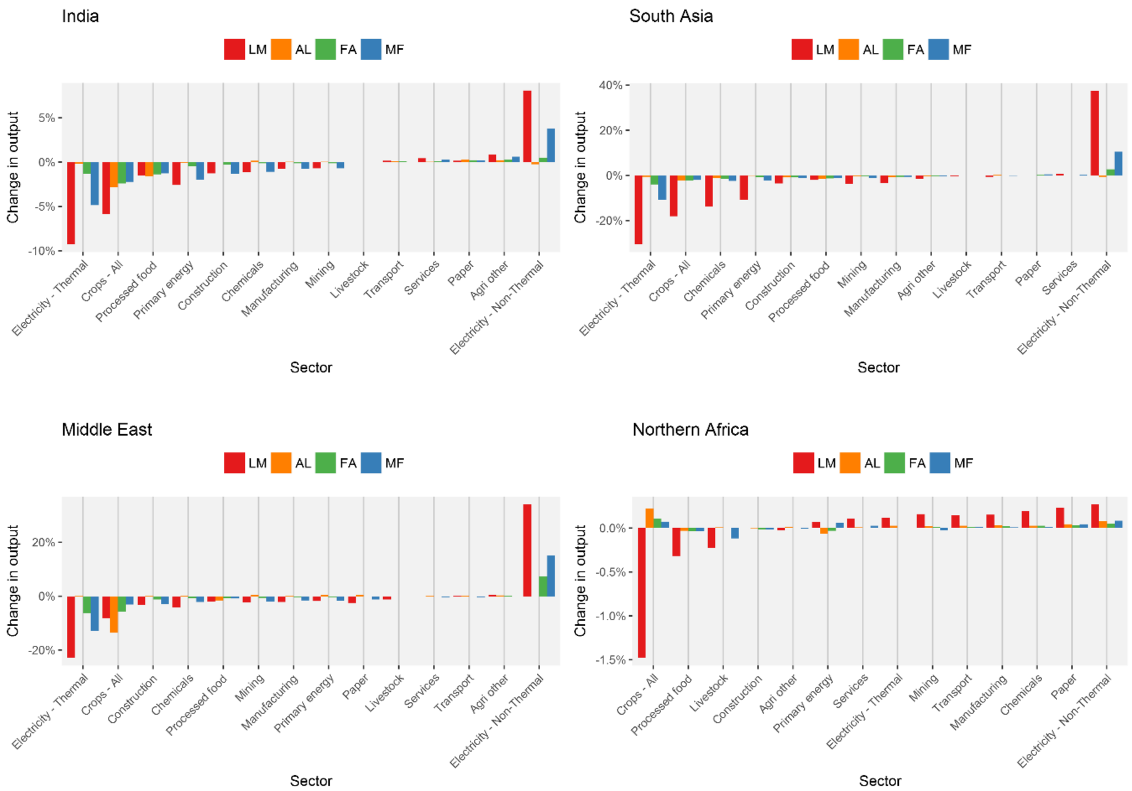

Figure 8.8 - Sectoral output impacts in water scarce regions in 2050 relative to the baseline

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8.4.1.2. Water scarcity rents

Water scarcity rents revealed by the market price of allocable water resources differ across methods (Table 8.6). The values obtained in the LM case are the highest as the competition between users is limited by the low mobility of water endowments. In the other cases, water scarcity prices are much lower with the smallest values obtained in the FA case. These values also represent the rents for the highest water allocative efficiency. For MF, as irrigation and non-irrigation water uses are completely separated into two water markets, the price for irrigation water uses are lower than those for non-irrigation. These differences mark the variation in marginal productivities between the two user types with possibilities of water re-allocation from crops to other non-agricultural sectors for further improvements in water allocative efficiency.

The AL case generates slightly higher rents than FA, although the GDP impacts are lower. Despite the potential efficiency gains in re-allocating some water volumes from non-crop sectors, the decline in crop output due to water scarcity determines a shift of other means of production (capital and labour) to other sectors improving the economic outcomes of the overall factor allocation. Furthermore, as water scarcity rents are not reflected in the cost structure of non-crop sectors, these will have a further competitive advantage as free-riders by expanding their water uses beyond the levels from the FA case.

Table 8.6 - Water scarcity rents in 2050 by region and by allocation method (\$/m^3)

Region	LM	AL	FA	MF	
				Irrigation	Non-irrigation
India	4.568	0.067	0.055	0.049	0.258
South Asia	4.460	0.042	0.040	0.037	0.129
Middle East	5.542	0.431	0.119	0.053	0.246
Northern Africa	0.962	0.003	0.003	0.003	0.064

8.4.1.3. Water withdrawal changes

The changes in withdrawals by self-abstracting sectors (and the changes in supplied water use by the underlying municipal and industrial water users) are determined by the trade-offs between these economic activities leading to different outcomes across the four allocation methods. Given the high water intensity of irrigated crops, the bulk of withdrawals reduction to reach the regional sustainability thresholds is ensured through a significant decrease in irrigation withdrawals (Figure 8.9). Nonetheless, for India and the Middle East, a noticeable demand cutback in volumetric terms also occurs in the second most important self-supplied sector - industrial water supply in India and municipal water supply in the Middle East.

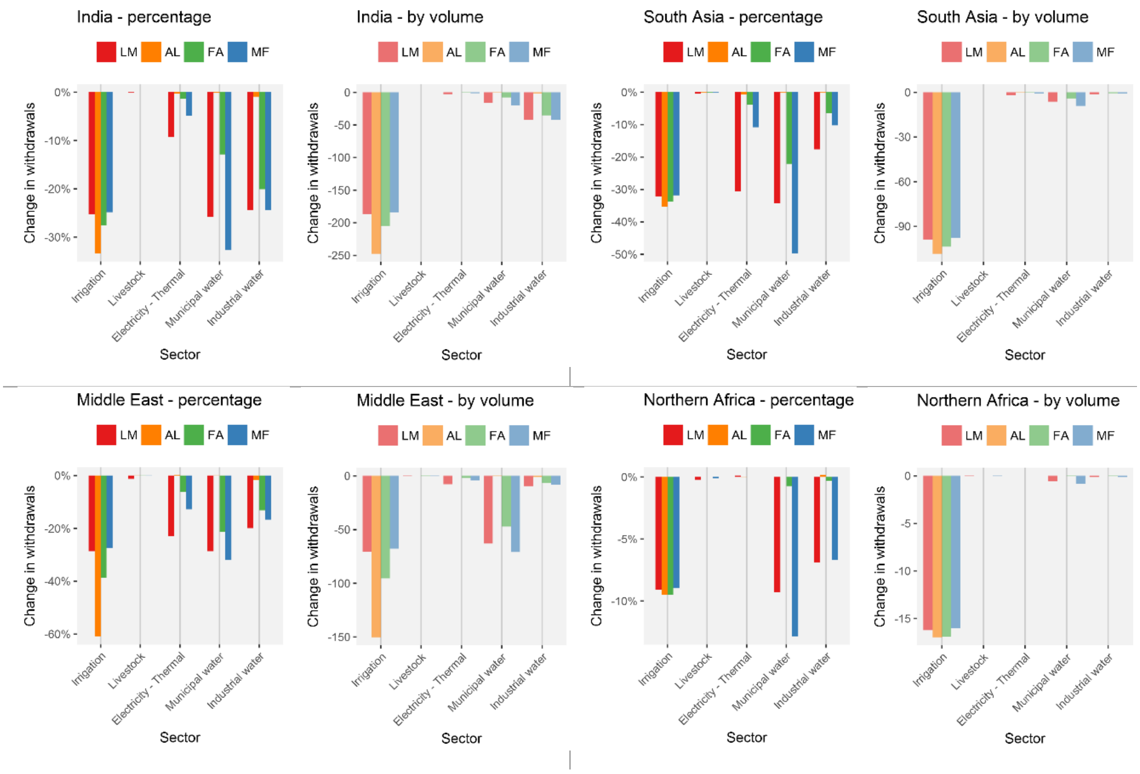

Figure 8.9 - Withdrawal changes by region and by self-abstracting sector in relative and absolute terms in 2050 relative to the baseline

In relative terms (change rate from baseline), in the LM method, municipal water withdrawals (despite a high water productivity) decrease at comparable rates with irrigation revealing thus a larger scope to reduce water demand of the underlying supplied users (services and households) compared to industrial water users. In the MF case, the higher flexibility in water allocation between non-crops users triggers a larger decrease in municipal water use to the benefit of the other sectors (thermal electricity, industrial water and livestock). Further on, the single water market configuration (FA case), determines a sharp reduction in water uses by irrigation and an increase in water availability for all other sectors (Middle East and South Asia) or notably for thermal electricity and municipal water (India). As baseline withdrawals for thermal electricity in Northern Africa are very low compared to other uses, water from irrigation is mainly redirected to industrial and municipal uses.

Changes in the water use patterns across the different crop types reflect the differences in crop water productivities[43]. Thus, water demand is considerably reduced in water-intensive crops (Figure 8.10). Withdrawals for *rice* and *wheat* in India decrease by more than 250km^3 (the equivalent of total required reductions) for *wheat* in South Asia by 60km^3 (half the total required reductions) , for *other crops* in the Middle East by 40km^3 (a quarter of total required reductions) and for *other crops* in Nothern Africa by 15km^3 (as much as total required reductions).

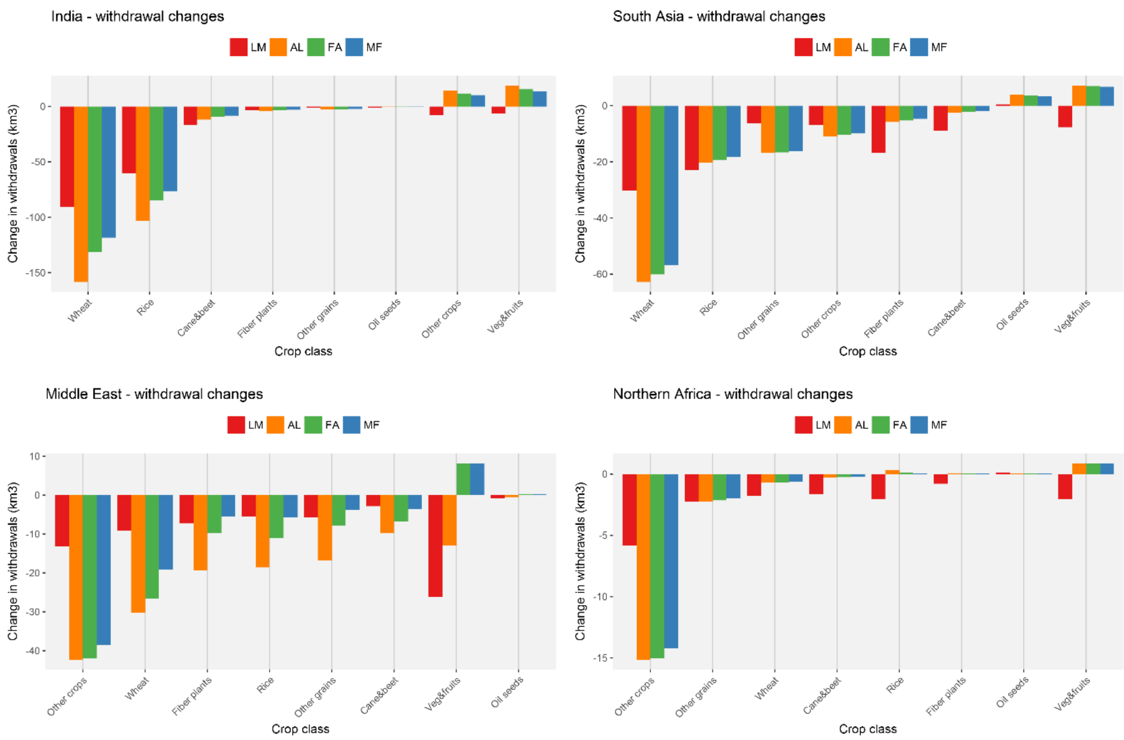

Figure 8.10 - Withdrawal changes by irrigated crop type in 2050 relative to the baseline

[43] see tables C1-C4 in the Annex C

8.4.1.4. Food security

Water scarcity highly impacts crop production with some differences across crop types (Figure 8.11). In India, *rice* and *wheat* are touched the most with decreases in output of over 15%; in South Asia, the same crops drop by more than 20%, whereas, in the Middle East, *other crops*, *fiber plants* and *wheat* can have a decrease of more than 30%. Northern Africa is less affected with only *other crops* having a marked decrease next to 10%.

The incidence of water deficits is dependent on the water allocation method with a clear contrast between LM and the other three variants. In this regime, crop production generally decreases across all crop types and regions, leading to an overall increase in crop market prices[44]. Irrigated production is constrained by water deficits, similarly to all non-agricultural water users, and by the lack of flexibility to re-distribute water across crop types. Although the fall-back from irrigated to rainfed production is possible, the substitution between the two growing methods is not sufficient to fully counteract the drop in output of irrigated crops (see Figure C1 in Annex C for changes in rainfed and irrigated production by crop class)

The other three allocation methods lead to a more noticeable re-allocations of water resources across crop classes marking the opportunity to improve the baseline water productivity across irrigated crops. The scarcity impacts over the output of some crops are thus alleviated to the detriment of others. In India, *rice* and *wheat* production further decline in favour of additional water use and implicitly an output increase in all other crop types. In South Asia, the highest output decline occurs for *other crops*, *wheat* and *rice*. In Northern Africa, a significant decrease in production is obtained for *other crops* with limited negative impacts for *cane&beet* and *other grains*. In the Middle East, water is re-allocated from most crops to sustain the irrigated production of *oil seeds* and *veg&fruits*.

The largest contrast is obtained in the AL case where competition over water use between crop classes is exacerbated by the unrestricted withdrawals outside irrigation. As the water volumes available for crop production are the lowest among all four allocation methods, the differences in terms of water productivity between crop classes become more evident. The Middle East is the exception where trade-offs are limited due to a lower variation in the baseline water productivity levels across crop classes but also to international trade (see virtual water trade section below).

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[44] Crop market prices correspond to the Armington good prices of each crop class and thus combine both domestic and imported varieties

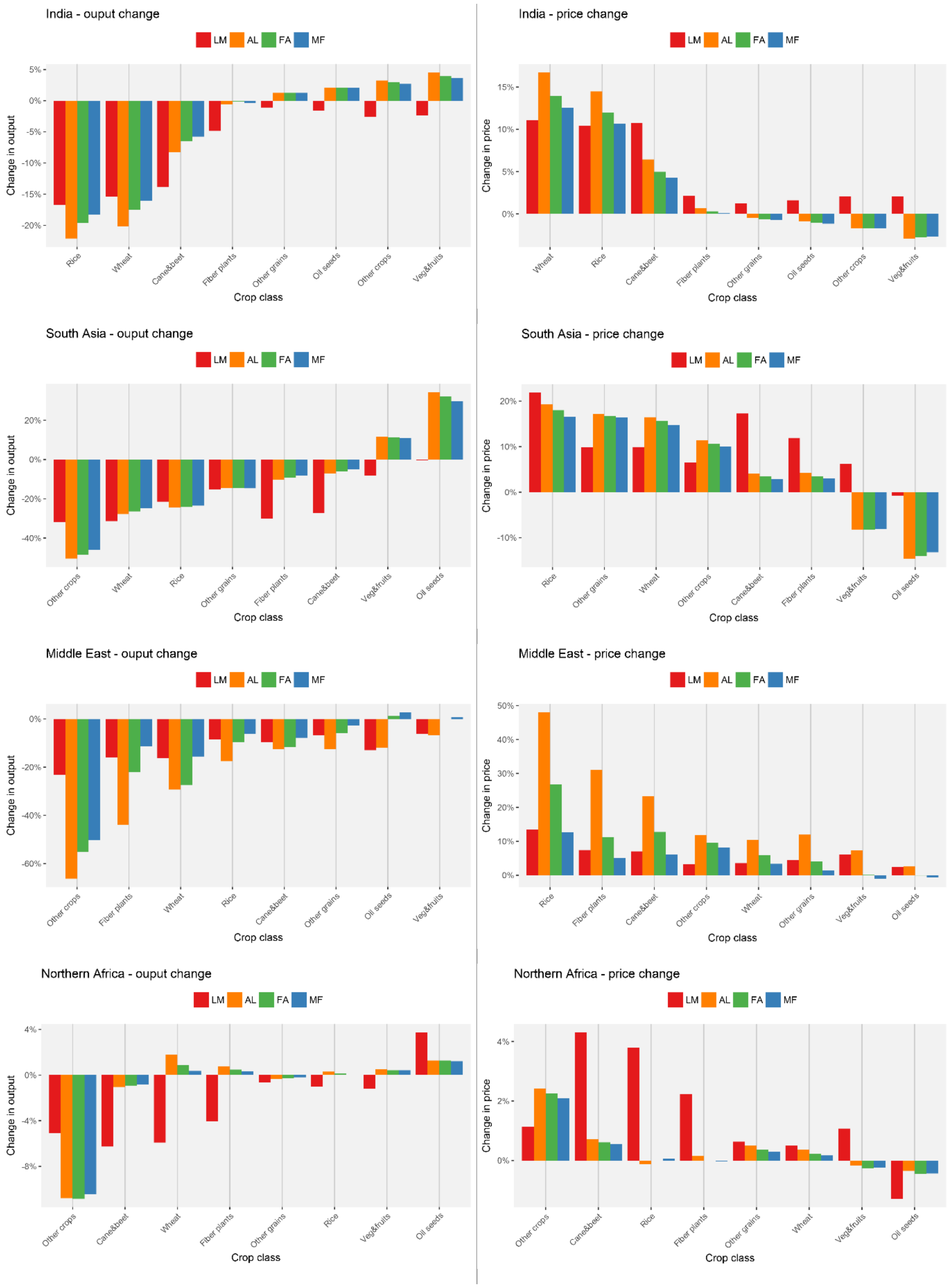

Figure 8.11 – Water scarcity impacts on crop production and prices in 2050 relative to the baseline

The water market fragmentation MF offers some protection to the crop production decline by limiting the volumes of water to be re-allocated to non-crop users. Hence the output and price outcomes are improved in MF compared to the single market FA case. The differences between the incidences of water scarcity across crop classes are also reduced. In this regard, AL and MF could be considered two opposing allocation methods - the former overlooks the importance of crops and food security, whilst the latter imposes a volume available for irrigation in spite of differences between crop water productivities and those of other water users.

The effect of the reduction in domestic production consisting in the increase in crop market prices is the most pronounced in India. This price response obtained across the four allocation methods is an indication that international trade does not have a significant role in reducing the food security impacts especially for the main crops of *rice* and *wheat*. As the imports dependency ratio in the baseline is low (Figure 8.12), the Armington specification of international trade prevents a significant expansion of imports despite the increase in market prices. In contrast, imports in the Middle East and South Asia have an offsetting effect on prices. The import dependency of *wheat* in the Middle East grows from 24% in the baseline to 36% for AL, and from 9% to 43% for *rice*. Similarly, in South Asia, the dependency grows from 18% to 33% for *rice*. Imports of other crop classes also increase in importance – *other crops* in South Asia; *oil seeds*, *fiber plants*, *other crops* in the Middle East and *other crops* in Northern Africa. These are all cases for which the baseline dependency ratio is non-negligible and for which output is negatively affected by regional water deficits.

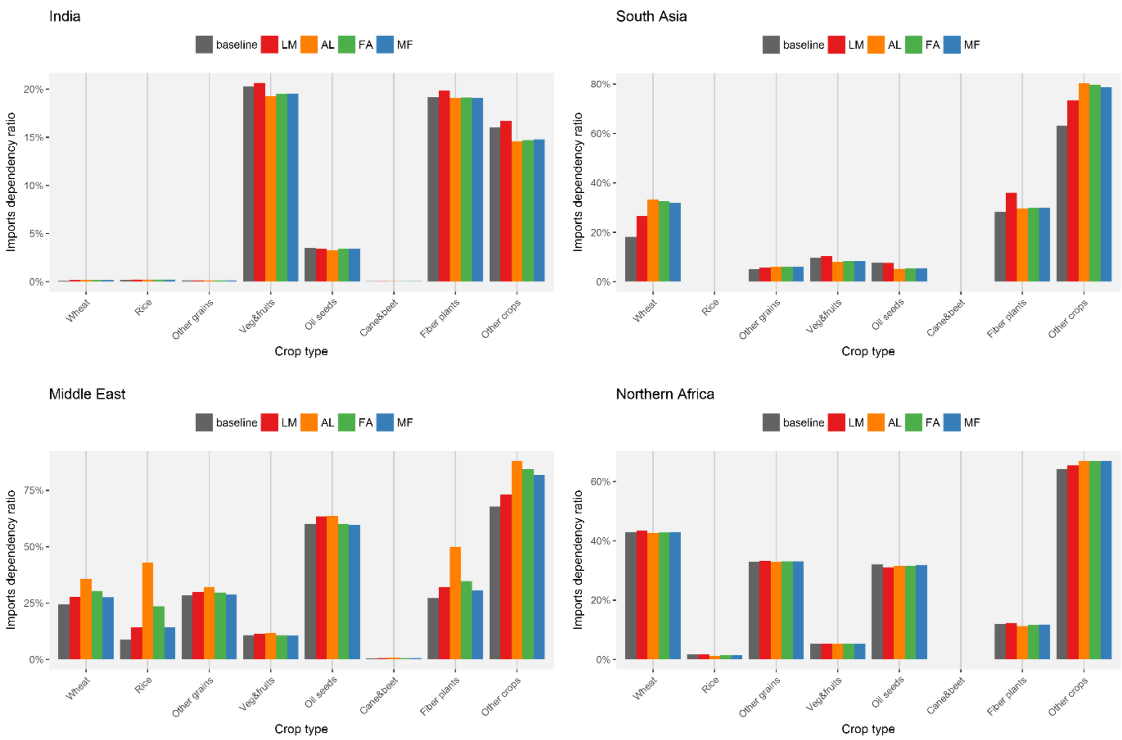

Figure 8.12 - Crop imports dependency ratio across allocation regimes by region in 2050

8.4.1.5. *Virtual water trade*

The impacts of water scarcity on global virtual water trade are limited to the flows of the four regions and are mostly driven by crop trade (Figure 8.13). The largest changes occur in the Middle East, where the net imports grow by 26km^3 in the AL case (Figure 8.14), or 7% of global virtual water trade in the baseline[45], indicating the importance of international trade in addressing the drop in domestic crop production. This increase in imports converts the region from being a net exporter of water (19km^3 of net exports in the baseline) to a net importer (8km^3 of net imports in AL). In Northern Africa, although the changes are small in absolute terms (1.5km^3), these account for 10% total required reductions in withdrawals in the region. South Asia has a noticeable increase in net imports only in the LM case determined by larger imports of *veg&fruits* and *fiber plants*. At the same time, some increases in net exports are obtained in India in the AL and FA case, as a marker that international trade can further increase the impacts of water scarcity, notably over food security, through exports of water-intensive commodities stimulated by increases in foreign demand.

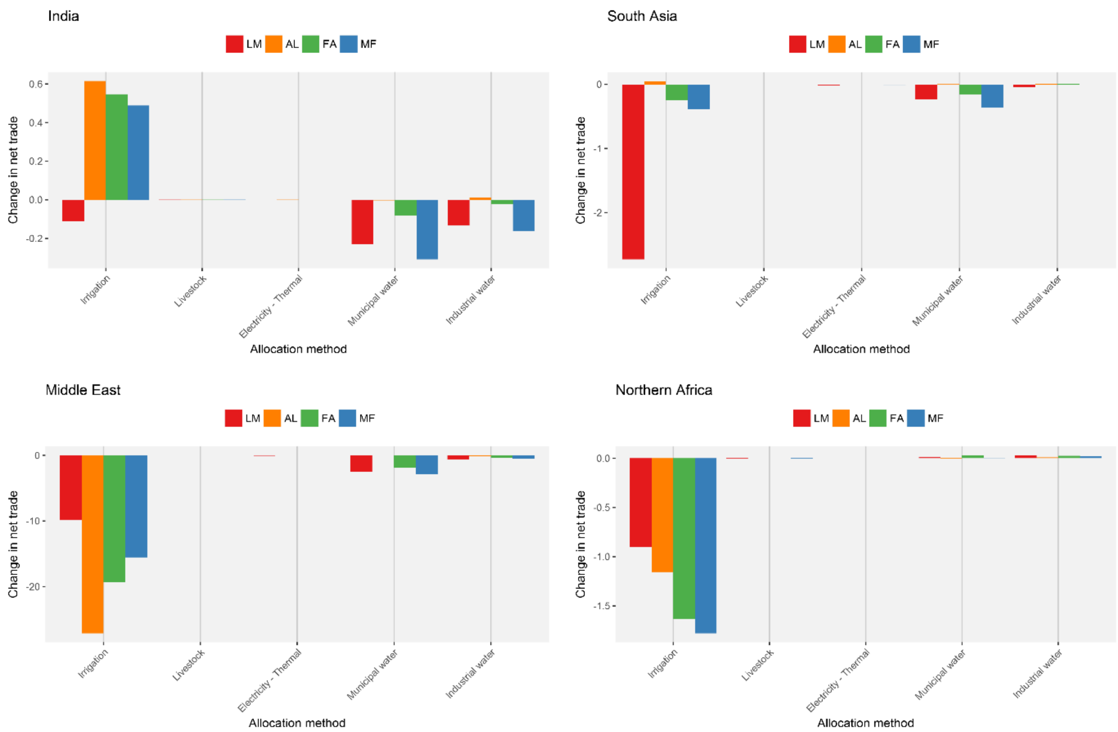

Figure 8.13 - Changes in net trade of virtual water by water use category in 2050 relative to the baseline

Other visible changes in the net trade of virtual water outside crops are mainly linked to commodities from activities using industrial and municipal water. As expected, AL does not have

[45] Global virtual water trade in 2050 for SSP2 is 372km^3 and includes the embedded water in both crop and non-crop traded commodities

any trade impacts given that water deficits do not constrain non-crop sectors. In the other allocation methods, virtual water imports associated with services (municipal water users) increase in all regions, except for Northern Africa, indicating international trade as a further adaptation mechanism to water scarcity. The same applies to the trade in commodities from industrial activities. However, the overall change in virtual water imports attached to industrial commodities is lower than that for services. Changes in the flows related to thermal electricity are limited by the low levels of electricity trade between regions in the baseline.

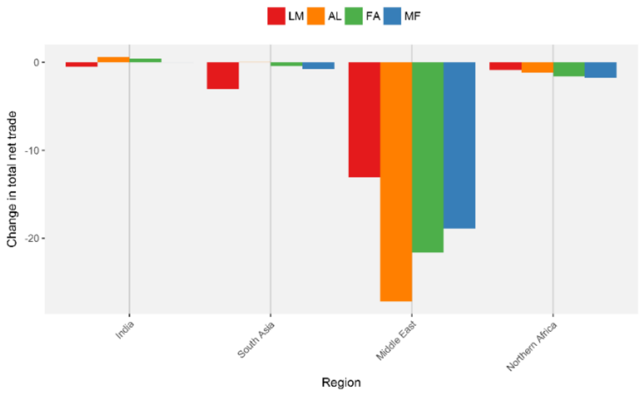

Figure 8.14 - Changes in regional net trade of virtual water by allocation method (in km^3) in 2050 relative to the baseline

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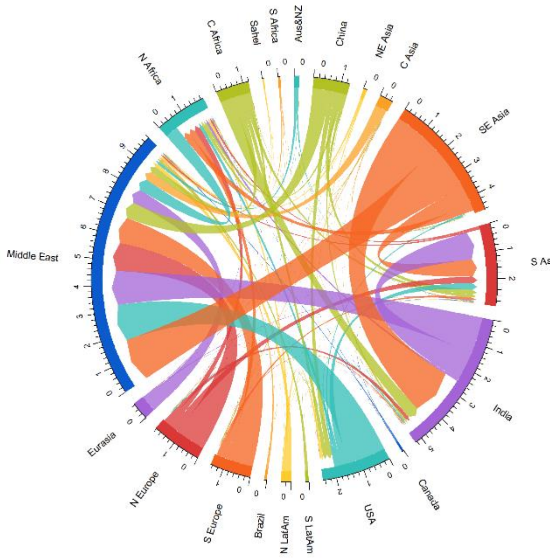
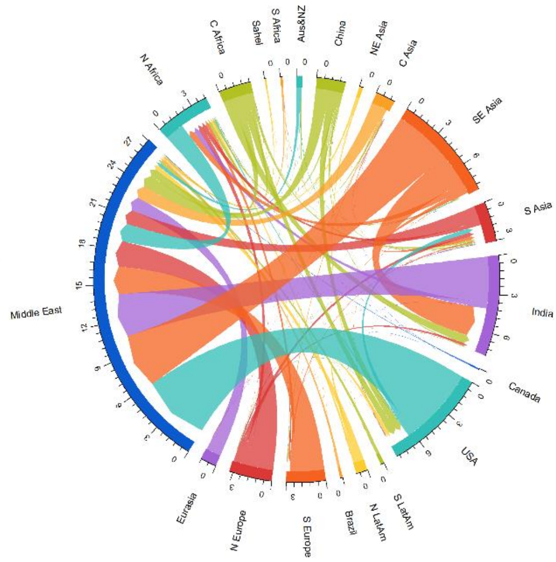
The Middle East has a dominant role in the virtual water trade changes with its net imports increasing across all its trading partners in all four allocation methods (Figure 8.15). The analysis of virtual water trade flows by pair[46] also shows the importance of this region in the net trade of the other three water-scarce regions - most increases in virtual water exports of India, South Asia and Northern Africa are absorbed by the Middle East. Other important sources of virtual water include the USA, Southeast Asia, Central Africa, and Northern and Southern Europe. Nevertheless, this growth in net exports of regions without water use constraints does not lead to a significant growth in water withdrawals in these regions – the total increase in 2050 outside water-scarce regions is 2.8 km^3 for LM, 4.5 km^3 for AL, 2.3 km^3 for FA and 2 km^3 for FM. This low expansion is an indication that instead of extending irrigated crop production, these regions redirect more domestic production towards exports or are predominantly exporting crops coming from rainfed production.

[46] The flows strictly refer to the blue water component of virtual water trade and, thus, do not include the green water volumes embedded in the trade of rainfed crops. Also, these flows are not reflective of changes in total net trade – changes in net trade at constant prices are shown in Figure C4 in Annex C.

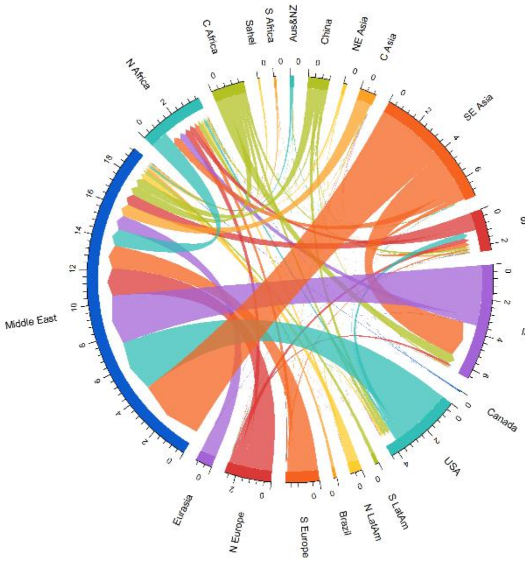
Limited mobility (LM)



Agriculture last (AL)



Full allocation (FA)



Market fragmentation (MF)

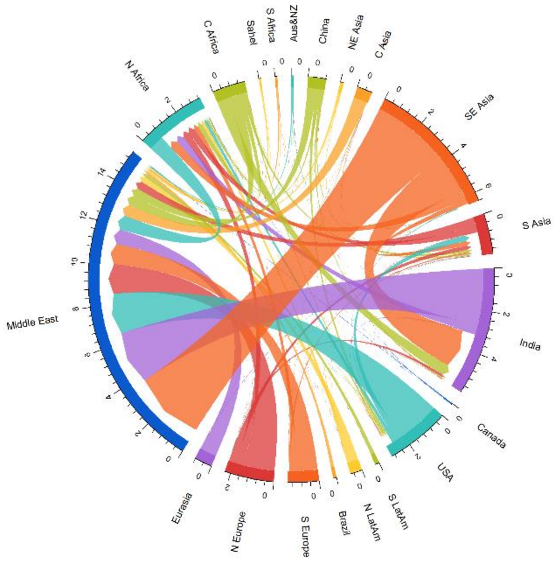


Figure 8.15 - Changes in virtual water trade flows of crops in 2050 relative to the baseline – net values by trading pair (in km3)

8.4.1.6. Sensitivity of results with respect to land conversion

Given the high impacts of water scarcity over crop production, the results are tested through a sensitivity analysis with respect to the adaptation of crop sectors through the channel of land conversion from the irrigated to rainfed type. This analysis is conducted by varying the transformation elasticity σ_{AL} which determines the convertibility of arable land into rainfed or irrigated land (see Section 4.4.4.3 from the RESCU-Water model description in Chapter 4). The elasticity value is changed from the base value of 2 to 0.1, 0.5, 5 and 10.

The GDP deviations from this change are not significant i.e. less than 0.1% (Figure 8.16) indicating a good robustness of the aggregate results in relation to this parameter. For low σ_{AL} values, deviations are largest in absolute terms but also negative for South Asia, confirming the region's significant agricultural sector in overall GDP. For the other regions, the GDP deviations are positive due to a further re-allocation of non-water resources away from agriculture to other sectors – see sectoral output deviations for India in Figure 8.17. In terms of crop production, restrictions in land conversion through a low elasticity value determine a re-allocation of land-related inputs (both rainfed land and irrigable land-irrigation inputs) across different crops with even positive impacts over some crop classes e.g. wheat in India (Figure 8.18, also see Figures C5-C7 in Annex C for the other regions). Nevertheless, from a food security perspective, the deviations obtained for staple crops (with values of up to 5%) are a fraction of the output reduction induced by water scarcity with the base parametrisation (20% or more for India, South Asia and the Middle East).

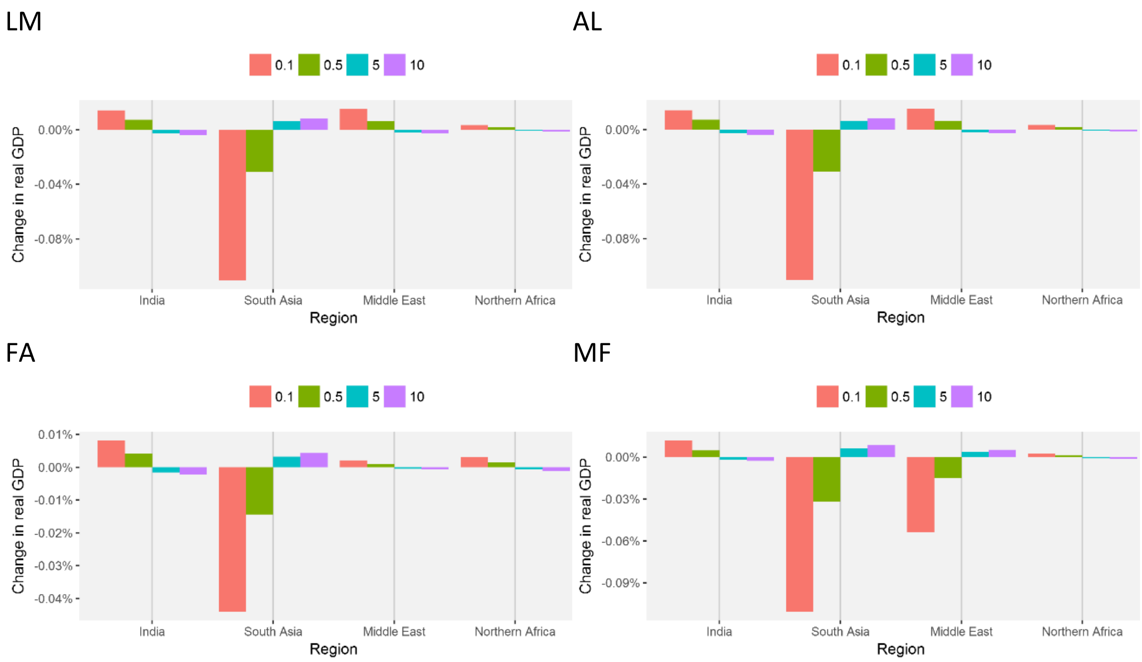


Figure 8.16 – GDP deviations from base parametrisation for 2050 - σ_{AL} sensitivity

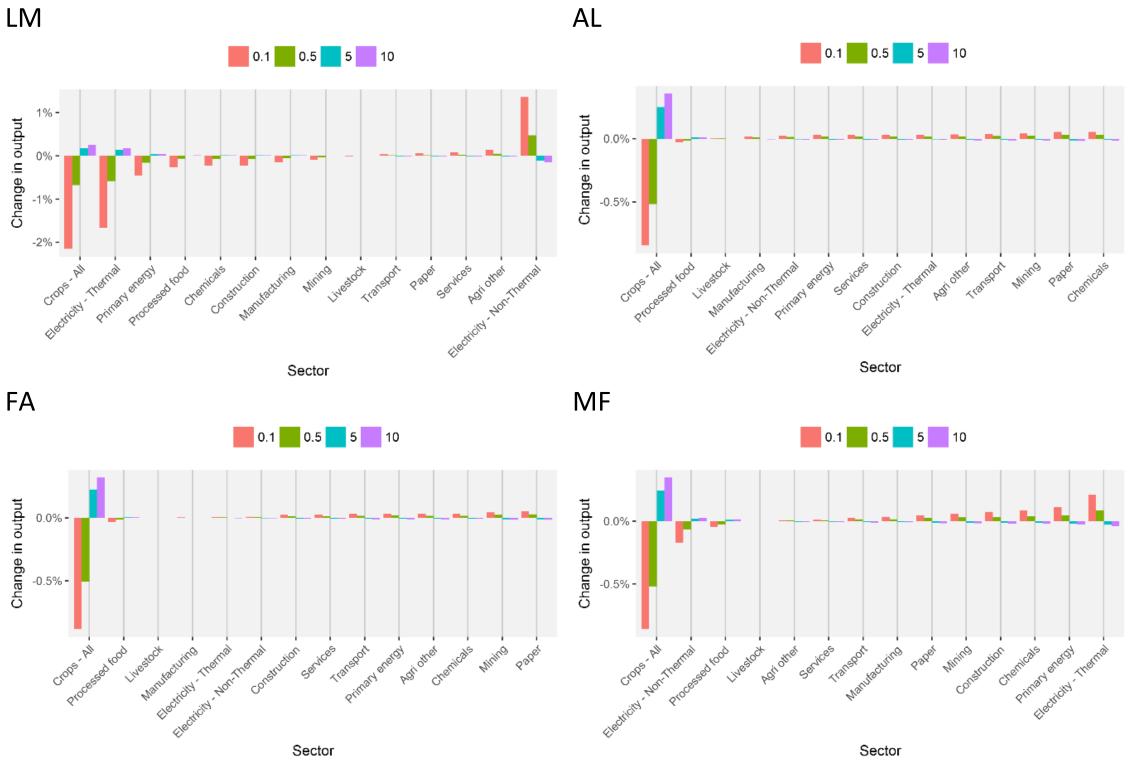


Figure 8.17 – Sectoral output deviations in India from base parametrisation for 2050 - σ_{AL} sensitivity

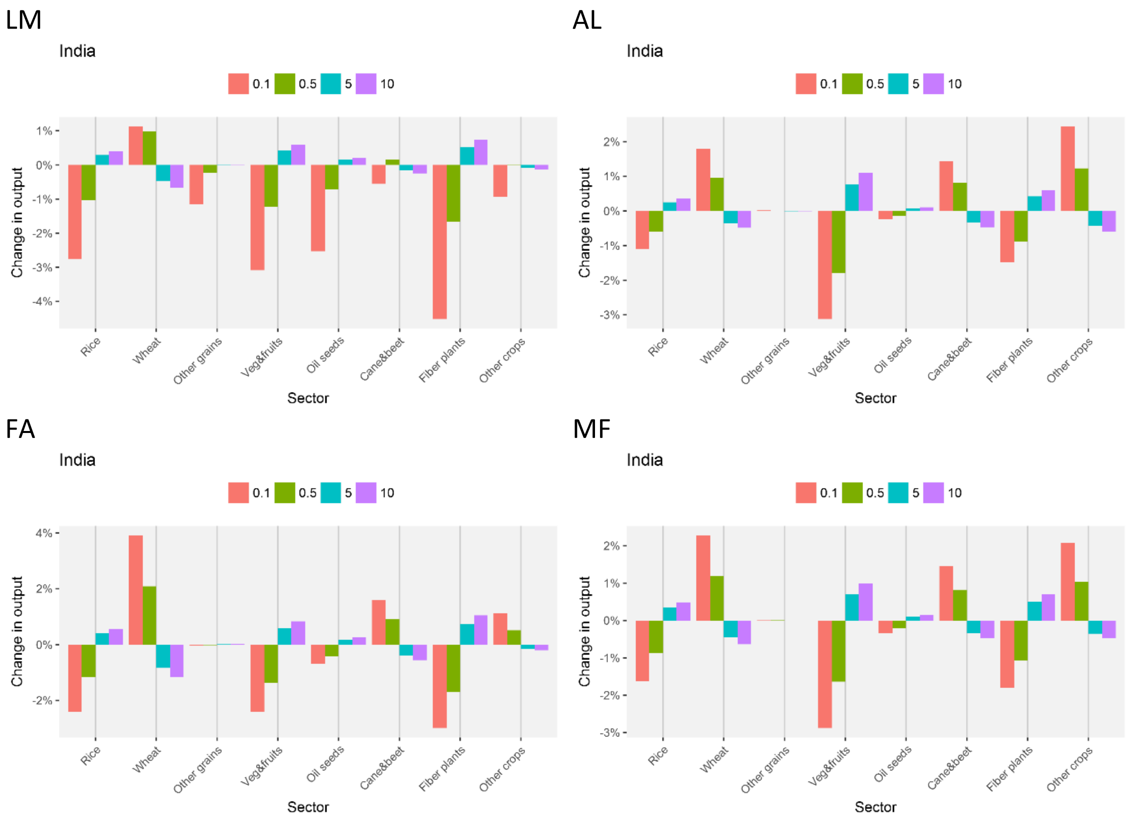


Figure 8.18 – Sectoral output deviations in India from base parametrisation for 2050 - σ_{AL} sensitivity

8.4.2. Climate change scenario results

Climate change considered through the crop yield, evapotranspiration rates and natural soil moisture impacts has a positive effect on GDP for India, the Middle East and Northern Africa across the two RCP scenarios (RCP 2.6 and 8.5) and the two allocation methods taken into account (FA and AL) - Figure 8.19. This is generally explained by the dominance of yield impacts over water demand in irrigation. In accordance with Chapter 7, yield reduction in these regions leads to a significant drop in crop output and consequently determines a reduction in irrigation water demand, in spite of changes in soil moisture taking place simultaneously notably in tropical regions. This reduction in crop production leads to water and other factors of production being freed up for use in other parts of the economy.

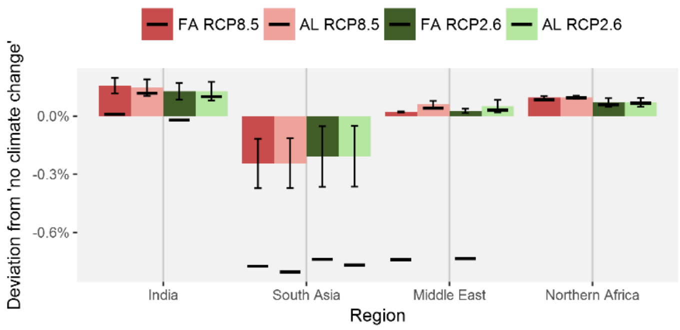


Figure 8.19 - GDP impacts deviations from 'no climate change' for 2050 – water-scarce regions

Note: The bar size indicates the mean values whereas the error bars represent the standard deviation based on the results using the datasets of the three GCMs (MIROC, HadGEM2 and IPSL); the black line measures the cumulated impacts of water scarcity from the 'no climate change' scenario and those with climate change.

In India, climate change leads to a reversing of GDP impacts of water scarcity from negative to positive in all cases but RCP 2.6 with FA. In the Middle East, the same happens for AL in both RCP variants, whereas in Northern Africa climate change adds positive impacts over GDP to the negligible impacts obtained under the 'no climate change' assumptions. In contrast, South Asia is further negatively impacted by climate change. This result is consistent with the observation from 'no climate change' that as food sectors continue to be important to the regional GDP, the negative impacts of climate change over crops are passed forward to the overall economy. This reliance on food production also determines a higher uncertainty of GDP impacts compared to the other regions.

Water prices fall in all regions in both allocation methods except the Middle East (both RCPs) and India (RCP2.6) – see Table 8.7. The decrease in price is an indication that overall irrigation water demand decreases due to the negative effects of yield changes. As obtained in Chapter 7, yield reduction impacts overall crop output with an implicit reduction in the use of irrigation. The impacts of climate change over water prices increase with CO_2 concentrations. At the same time, the alternative allocation methods lead to differences in price changes only India and the Middle East. In the Middle East, the increases in the water price are explained by an irrigation water intensification.

Crop production bears most of the negative impacts of climate change which are increasing with GHG concentrations (Figure 8.20). The processed food sector is also affected through knock-on effects of changes in crop output. The other sectors are generally positively impacted in India, Middle East and Northern Africa, whereas output is decreasing in several non-food sectors in South Asia.

Table 8.7 - Water scarcity rents in 2050 by RCP and allocation method (\$/m³)

Region	**RCP8.5 - FA**	**RCP8.5 - AL**	**RCP2.6 - FA**	**RCP2.6 - AL**
India	0.046 (-16.1%)	0.06 (-10.6%)	0.055 (0.4%)	0.068 (0.4%)
South Asia	0.037 (-7.1%)	0.039 (-7.2%)	0.038 (-3.9%)	0.04 (-4.0%)
Middle East	0.128 (7.5%)	0.476 (10.4%)	0.124 (4.2%)	0.464 (7.6%)
Northern Africa	0.002 (-47.0%)	0.002 (-46.8%)	0.002 (-29.0%)	0.002 (-28.9%)

Note: Values in brackets represent changes relative to the 'no climate change' results of the two allocation method

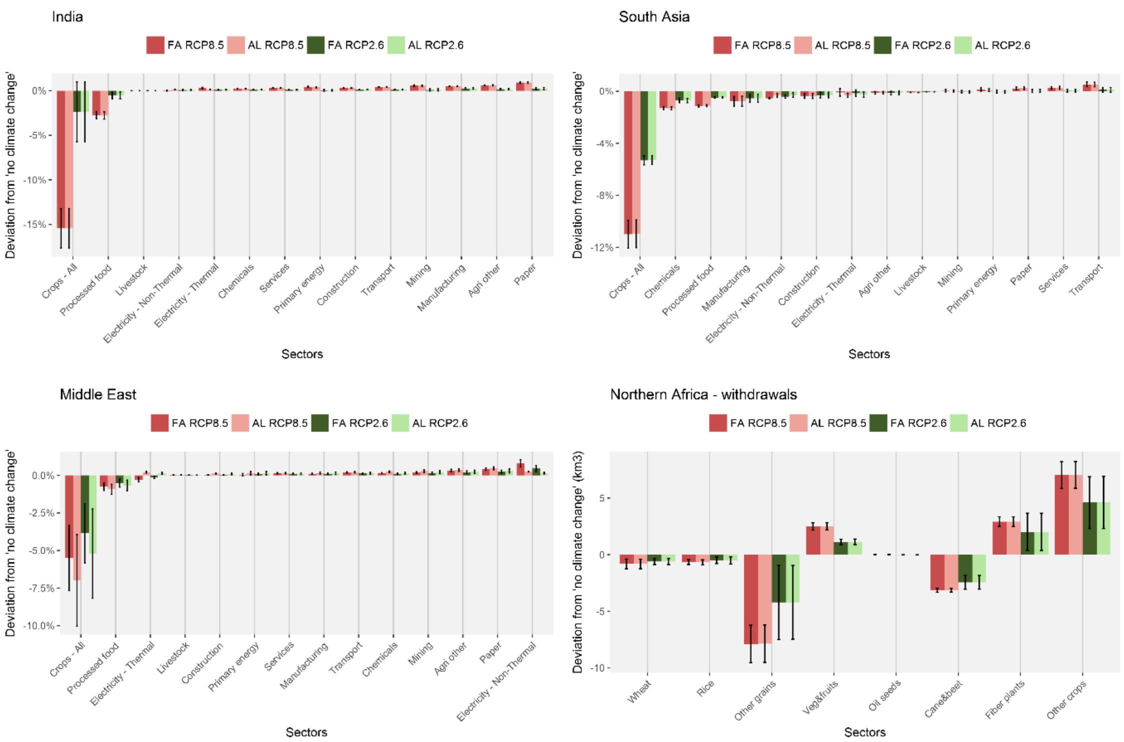


Figure 8.20 – Sectoral output impacts deviations from 'no climate change' in 2050 – water-scarce regions

As determined in Chapter 7, climate change without accounting for the CO_2 fertilisation effect has an overall negative impact on crop performance, determining a significant drop in production levels of the different crop classes (Figure 8.21). The crop production mix obtained in the ‘no climate change’ scenario is thus further altered. Crop classes negatively affected by water scarcity alone are further impacted by climate change, whereas the positive outcomes previously obtained for crops with higher water productivities (*veg&fruits* and *oil seeds*) become negative in most cases.

Even in RCP2.6, *wheat* output drops by an additional 5% in India and the Middle East, and by 10% in South Asia, whilst *rice* production drops by 5% in India and South Asia. In RCP8.5 the cumulated impacts of climate change and water scarcity lead to significantly higher decreases in output, leading to a doubling of the negative effects for many crops of the demand-driven water scarcity taken alone. Thus, overall *rice* and *wheat* production decrease by a third relative to the baseline in India; in South Asia, production of *wheat* halves and that of *rice* reduces by 40%. In the Middle East, crop output changes are much more dependent on the water allocation method, and thus the production of *wheat* and *other grains* reduces by more 25% in the AL case and by more than 10% in the FA case. In Northern Africa, crop production changes relative to the baseline are driven mainly by climate change and less by water scarcity except the *other crops* class.

Due to alterations to soil moisture and crop water intensities, the crop-specific changes in output do not lead to similar reductions in withdrawals. Therefore, an irrigation water intensification can be seen for all crops except *cane&beet* in India and South Asia, for *veg&fruits* in the Middle East, *veg&fruits*, *other grains* and *other crops* in Northern Africa – this intensification is observed by a concomitant reduction in output and an increase in water demand in Figure 8.21.

However, the overall changes in withdrawals for irrigation are not significant and only determine marginal re-allocations of water between the self-abstracting sectors. In India, irrigation withdrawals decrease most by $3km^3$ in FA RCP8.5 and water resources are re-allocated to municipal and industrial water supply. In the Middle East, water demand for irrigation in the Middle East increases by $2km^3$ in FA RCP8.5 through a re-allocation from municipal water supply (see Figure C5 in Annex C). Therefore, the changes in crop water productivity due to climate change induce a re-distribution of water uses mostly across crops and not between larger sectors of the economy.

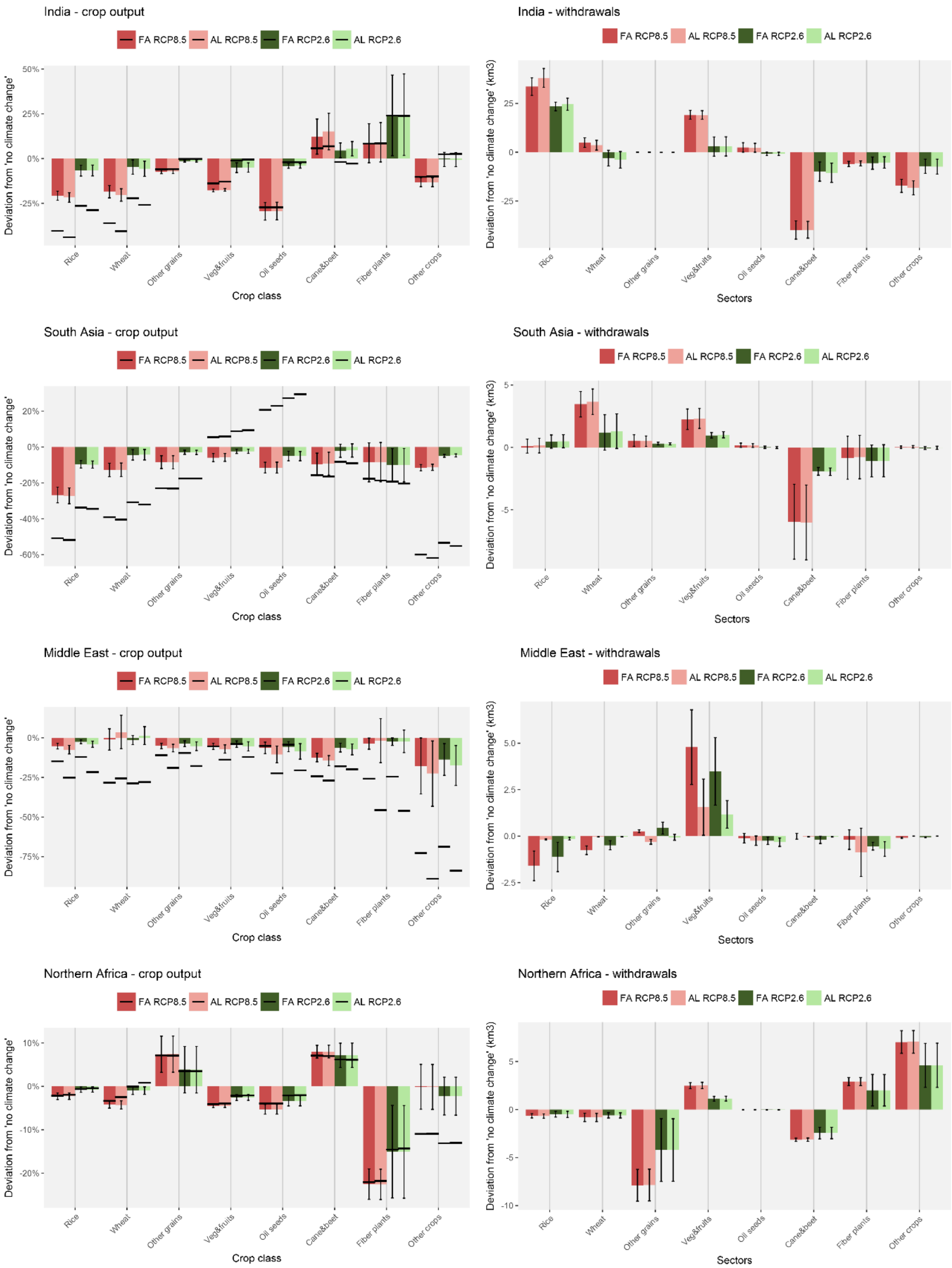


Figure 8.21 - Crop output and withdrawals deviations from 'no climate change' in 2050

Note: the line bars represent the cumulated impacts of water scarcity and climate change over crop output

8.5. Discussion

8.5.1. Economy-wide impacts without climate change

The obtained results indicate different outcomes for economic activity, welfare and food security across the four allocation methods considered. In essence, the LM method leads to a general decrease in economic activity with limited re-adjustments of production as a consequence of water availability constraints acting on water-intensive sectors. The AL allocation determines a neutral impact over non-food sectors and, depending on the exposure of the economies in water-scarce regions to food sectors (crops and food processing), determines a low impact on GDP, as non-crop water users act as free-riders. However, in the AL case, production of staple crops (*rice*, *wheat* and *other grains*) is the most significantly impacted with important implications for food security. In the MF variant, the separation of water uses by crop and non-crop users enables the availability of a guaranteed water volume for crops and therefore ensures some protection for food production – in this case, alterations to the crop production mix and changes in crop prices are the lowest. Nevertheless, MF leads to higher GDP impacts as the divergence in marginal water productivity between crops and other sectors remains significant, as revealed by the fourfold difference between the water scarcity rents of the two user types. In the FA case allowing full mobility of water resources across economic, the GDP and food security impacts are moderate relative to the other allocation methods.

GDP versus food security

Table 8.8 summarises these findings and reveals two important contrasts in the incidence of water scarcity across the two dimensions of GDP and food security. The first contrast is between diversified economies (India and the Middle East) and those with a significant food sector in the regional GDP (South Asia). Economies with a sizeable agricultural and food processing sector do not show an important variation in GDP impacts across the three allocation methods based on water productivity differences (AL, FA, MF) – the drop in crop production has a significant negative knock-on effects over the other sectors. The second contrast applies to diversified economies and refers to the difference between these allocation methods and that of a more prescriptive allocation (LM) where most water uses are pre-determined. For the former group of methods, the GDP - food security impacts are antisymmetric, producing either "high-low", "moderate-moderate" or "low-high" outcomes. For the latter method (LM), the impacts are high across both dimensions. These observed trade-offs between GDP and food security make a case for a general equilibrium approach rather than a partial equilibrium crop-focused analysis. Water scarcity and the region-specific sectoral interlinkages lead to different outcomes depending on the allocation method used.

Table 8.8 - GDP and food security impacts comparison across economy types by water allocation method

Economy type	GDP impacts			Food security impacts		
	High	Moderate	Low	High	Moderate	Low
Diversified economy	LM, MF	FA	AL	LM, AL	FA	MF
Significant food production sectors	LM	AL, FA, MF	n/a	LM, AL	FA	MF

These trade-offs are essential in the discussion related to the impacts of water scarcity over prosperity. By only taking into account GDP deviations from the baseline, it could be inferred that water deficits effects are not so much a matter of availability but one of how water resources are managed considering the relative water productivities of users. This conclusion is also coming out of the economic modelling results in World Bank (2016) and is captured here through the differences between LM and the other three productivity-based methods. However, the results also reveal that the food security impacts are large and could thus be felt much more by the low-income households and by the rural population whose livelihoods depend on crop production.

Drivers of GDP impacts

The economy-wide impacts of water scarcity are strongest in conditions of limited possibilities of water re-allocation across economic activities (LM case) with values close to 2% of GDP for the Middle East and South Asia. The most affected areas are the self-abstracting sectors (crops, water distribution sectors and thermal power), with cascading effects on the water-intensive industries supplied with industrial water (primary energy, chemicals, manufacturing, mining and paper). However, livestock production is much less affected due to the sector's high water productivity compared to all other water users. The re-allocation of non-water factors of production (labour and capital) in sectors with low or no water inputs is limited with only singular cases of visible increases in output (generally non-thermal power).

Nevertheless, these negative effects are alleviated by the substitution effects which can occur between similar activities (irrigated and rainfed crop production, thermal and non-thermal power generation). Therefore, whilst the substitutability between varieties of market commodities remains valid[47], the capacity of production to adjust over time especially in power generation systems is important. The model assumes a perfect mobility of capital and labour. Hence, the switch in production from one type to another is frictionless. However, considering

[47] Irrigated and rainfed crops could be considered homogenous and therefore close to perfect substitutes; thermal and non-thermal power can be imperfect substitutes as, for instance, thermal power technologies could be a more reliable solution for baseload power production whereas non-thermal (solar and wind) technologies produce electricity intermittently.

the long lifetime of power generation assets, the perfect mobility of capital could be challenged through a putty/semi-putty technology or a CET capital mobility specification. This imperfect mobility assumption could thus further increase the economic impacts of water scarcity over the overall power generation with knock-on effects across the other economic sectors.

Another alleviating factor is the household recycling of revenue of water rents - the loss of income due to a water-constrained economic activity is partially counterbalanced by an increase in income from scarcity rents. This revenue recycling is a different specification than that in Roson (2017) where water scarcity translates into a loss in total factor productivity across sectors based on the initial relative water productivities, and thus household income is generally reduced.

Another important determinant of GDP impacts that also affects welfare and food security is the combination of the distribution of baseline sectoral water productivities and the size of water demand in low productivity sectors. Regions with low productivity sectors also accounting for the largest share of withdrawals (India with *rice* and *wheat*, Northern Africa with *other crops*) make most of their water demand reductions in these activities. Therefore, the economic impacts are concentrated within a small number of crop growing activities leaving the other parts of the economy less water-constrained. Again, the negative impacts on irrigated production are partially offset through substitution with rainfed production, and therefore the localised effects on a few economic activities are further attenuated.

The obtained changes in withdrawals to meet the sustainability threshold reflect both differences in water productivity and the adaptability of specific sectors to water deficits. Among the self-abstracting sectors (which treat water as a perfect complement to other inputs), livestock and thermal power see the lowest reduction in withdrawals as an indication of their low water intensity. At the same time, in spite of a superior water productivity, municipal water is a more important source of demand reduction than industrial water, marking the larger flexibility of the underlying municipal water users (services) to substitute water with other inputs.

Notably in diversified economies, the size of GDP impacts is determined by the sectoral impacts of water-intensive industrial users. In the model specification, these sectors have a low substitutability of water with other inputs. With an increased adaptability which can come from the adoption of more water-efficient production processes, the impacts could be significantly reduced (Figure 8.22) as indicated by the results of a sensitivity analysis on the key elasticity of substitution σ_{ND2} between industrial water inputs and all other intermediate goods (see the analysis in Annex C). Therefore, the magnitude of effects on economic activity in a scenario with a low flexibility in the technological choices warrants more research into the sector- and region-specific means of improving water productivity in industrial activities. An example of how the water savings potential varies between regions is given in McKinsey (2009 p.73).

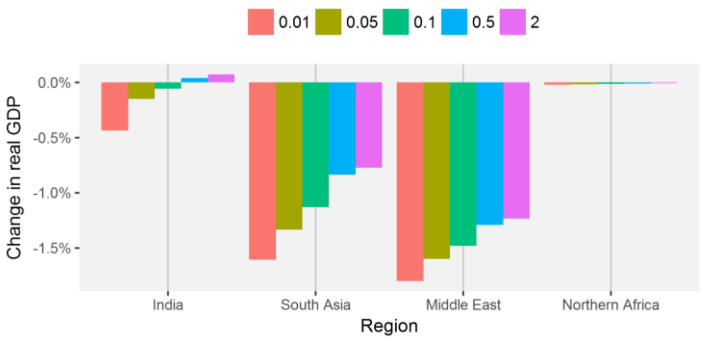


Figure 8.22 - Real GDP impacts in 2050 in water-scarce countries by σ_{ND2} value - LM allocation method

Note: the 0.01 value is the base value used in the Results section

Significance of international trade

The attenuating effect of international trade on food availability is also limited. This is conditioned by the flexibility in switching consumption from domestic to foreign varieties, given the Armington specification of trade. Regions which already have a high share in imports of water-intensive commodities (Middle East and Northern Africa) benefit from more virtual water inflows, whilst regions being self-sufficient from a crop production standpoint have a limited import expansion. The Armington elasticities[48] are thus a blocking factor to the expansion of imports of water-intensive commodities where the baseline regional imports are low. Furthermore, the simultaneous occurrence of water scarcity across regions leads even to an increase in pressure over low water-productive sectors in some regions in favour of other regions e.g. due to the size of initial trade links, India exports irrigated crops to the Middle East impacting, thus, its own food security.

Comparison to other studies

The GDP and EV impacts obtained in Roson (2017) are significantly higher than the results obtained in this chapter, with a GDP decline, for instance, at or well above 4% in the Middle East[49]. An explanation for these differences consists in the much larger water deficits considered and is justified by higher unconstrained withdrawals in water-scarce regions by 2050. These

[48] Values derived from the GTAP database
[49] Depending on the water allocation scenario; this decline could be as much as 14% in the low mobility case

differences are mainly coming from a considerable expansion in irrigation water demand as this is calculated on a "top-down" basis (see discussion in Chapter 3 section 3.3.2.8). Another explanation is that in Roson (2017) there are relatively low means of endogenous adaptation to water scarcity as output is constrained by pre-determined changes in total factor productivities. In RESCU-Water, as discussed above, the advanced specification of water uses and the substitution possibilities between low and high water-efficient varieties of the same commodity allow for more resilience of the regional economies to water scarcity.

In the static-comparative simulations using GTAP-W1 (Berrittella et al. 2007), regional water demand is reduced by only a small fraction, leading to much lower GDP and sectoral impacts. Only a few sectors across water-constrained regions exceed a negative impact of 1% (mainly crops). At the same time, similarly to RESCU-Water, the sectoral output results indicate a re-allocation of non-water resources across economic activities towards sectors with little or no supplied water inputs.

8.5.2. Demand-driven water scarcity and climate change impacts

The overlapping effects of water scarcity and climate change lead to a further deterioration of food security prospects. The impacts are felt even for the low RCP2.6, whilst the decrease in output of staple crops doubles compared to the 'no climate change' scenario, indicating that demand-driven water scarcity is just as important as climate change impacts despite higher precipitation levels in some of the water-scarce regions.

The effects of climate change are translated into the model not only in relation to yield impacts (land input productivity) as done in previous CGE modelling efforts but also by taking into account alterations to irrigation water intensities coming from changes in evapotranspiration rates (temperature-induced) and changes in soil moisture (influenced by precipitation). Therefore, compared to Chapter 7, both yield and irrigation water productivity act as shocks and can thus influence crop output and prices in opposing directions.

The reductive effect of climate change on irrigation water demand for the four water-scarce regions is not felt through important re-allocations of water resources to non-crop users compared to the 'no climate change' scenario. This lack of response is due to the size of water withdrawals reduction required (mostly obtained through an important decrease in water demand in irrigation) which is generally larger than the obtained decrease in water demand for crops due to climate change alone, as obtained in Chapter 7. Therefore, climate change largely induces a re-allocation of water resources between the different crop classes given the crop-specific yield and water productivity impacts.

8.5.3. Limitations

Whilst the incidence of water deficits is determined for a number of regions, some other regions were not considered as water-scarce due to their more localised water deficits (China, Southern Africa, USA, Australia). The coupling of RESCU-Water with other advanced hydrological models comprising spatially-detailed information on water-use constraints relative to the topology of users could enable the inclusion of other regions in the analysis. Furthermore, the water supply limits imposed are applied to a regional level and do not take into account basin-specific constraints even in the four regions considered. Hence, in this regard, a further qualification of sustainable withdrawal thresholds could also be done using spatial modelling.

The water deficit calculation is partially based on top-down demand projections (industry and municipal water use) which are not empirically validated but are derived by building on previous work. The comparison of results shows a good agreement for global withdrawals and developing regions. However, some differences occur regarding the industrial water uses in currently developed regions. As the simulations do not imply constraining any of the high-income regions, the CGE scenario results are not influenced by a potential overestimation of water uses in industrialised regions. At the same time, there are significant differences even between projections with empirical validation (see Wada et al. 2016) indicating that more work should be done in the direction of establishing water use baselines for economic modelling simulations.

The positive impacts of climate change on GDP under water scarcity in diversified economies show that the effect of non-water resource re-allocation is strong, and indicates that climate change is largely an issue for food security. Nevertheless, it should be acknowledged that other sectors could also be directly impacted by changes in environmental operating conditions. For instance, as outlined in Wada et al. (2016), the demand for water for thermal cooling could increase with ambient temperature. Furthermore, the impacts in this chapter exclude the implications of climate change for the supply of other factors – the reduction in capital and land availability and that of labour productivity as in Parrado et al. (2017) or Bosello et al. (2007).

Regarding food security impacts, the conclusions are derived from model results on crop availability and prices. Details on the influence of crop production mix on malnutrition are not available as these would require a further consideration of the relationship between the food value chain informing the final food demand composition and the calories intake by different population groups.

Regarding the coverage of allocation methods, the model mostly makes use of differences in water productivities in re-distributing available water resources to the different users. At the same time, the different principles used allow for a prioritisation of certain users to the detriment of others. A further analysis could be conducted in the direction of food security policy by considering among other things programmes for increased irrigation water efficiency or a larger availability of water for crop production (possible through the MF method by shifting the burden of reducing withdrawals to non-agricultural sectors). However, considering the global level of the analysis in this chapter, it would be difficult at this stage to introduce other relevant methods which do not embed water productivity information but are mostly prescriptive in nature.

8.6. Conclusions

This chapter used the future evolution of unconstrained water demand driven by socioeconomic development as a starting point to determine the impacts of water deficits on economic activity, welfare and food security. These impacts were measured across three climate-change variants – no climate change, RCP2.6 and RC8.5. By comparing the unconstrained demands with regional thresholds for sustainable withdrawals, four regions emerged as water-deficient due to their growth in water demand across five water use types (irrigation, livestock, thermal cooling, industrial water and municipal water) – India, South Asia, Middle East and Northern Africa. The reduction in water demand in these regions was enabled using four different water allocation methods.

In a world with perfect water mobility, an allocation based on differences in water productivity between sectors leads theoretically to water allocative efficiency (FA method). However, this does not guarantee the best aggregate economic outcome due to the interaction with other factors of production. Changes in sectoral output due to water scarcity also determine a re-allocation of non-water resources across the economy. With agriculture also having a low factor productivity of capital and labour, the water allocation methods determining the highest re-distribution of resources to the other sectors lead to the lowest GDP impacts. Therefore, the method treating crops as lowest water priority users (AL method) improves most the output prospects of non-food sectors to the detriment of crop production and food processing.

At the same time, the scale of economy-wide impacts is dependent on the weight in GDP of sectors with low-water productivity (economic diversity), the size of water uses in these sectors and the flexibility of important water users to substitute from water inputs in conditions of water scarcity. Furthermore, given the Armington specification adopted in RESCU-Water, the use of international trade as a means to alleviate the impacts of water deficits is conditional upon the baseline import dependency of water-intensive commodities– the lower the ratio, the lower the changes in net imports of virtual water trade under water scarcity-, and on the value of the Armington elasticities .

The food security impacts are pronounced across all methods considered, with the lowest negative outcomes obtained through the isolation of water demand in irrigation from all other water uses (MF method). In the model simulations, this implied a uniform reduction in crop and non-crop water availability. More protection to the food value chain could be obtained by ensuring more water availability for crop production and less for other uses. However, this would implicitly lead to a higher negative GDP impact as a trade-off.

The combined effects of climate change and water scarcity over food security indicate water deficits just as important (in RCP8.5) or even more important (in RCP2.6) than the climate-induced changes in crop growing conditions. Hence, the crop production mix is further altered with significant drops in the production of grains in India, South Asia and the Middle East. The two allocation methods considered (FA and AL) do not lead to significant differences in outcomes.

By using a comprehensive CGE framework focused on the economy-wide uses of freshwater, the results in this chapter offered an extended insight into the economic impacts of alternative water allocation regimes. The results presented here go beyond most of the previous work which focused on the relationship between water scarcity and agriculture and which only took one water management method into account (Calzadilla et al. 2013; Liu, Thomas W. Hertel, et al. 2016; Ponce et al. 2016). Furthermore, the analytical outputs are an important expansion into the topic of trade-offs between aggregate economy-wide impacts and food security, an area under-explored even in the most recent economy-wide CGE modelling work.

Chapter 9. Concluding discussion

9.1. Thesis overview

This thesis aimed to explore the economy-wide implications of the future demand-driven blue water scarcity across world regions. The analyses surrounding this aim were conducted using a global CGE modelling framework and were undertaken through several stages to build up a representation of the main drivers affecting the evolution of global water demand – socioeconomic development and climate change. As reviewed in Chapter 3, past efforts to model water uses across the economy using multi-regional and multi-sectoral models are now dated, with most work in the past decade dedicated to the analysis of water scarcity in crop production alone. At the same time, the water accounting in the RESCU-Water model used took advantage of the recent advances regarding the calculation of water use by the broader user categories.

Given the dominant role of irrigation for the present and future state of anthropogenic pressure on freshwater resources, the consideration of water demand drivers in this area was developed in greater detail. Water demand in irrigated crop production was calculated "bottom-up" using an advanced specification of the global crop systems in which rainfed and irrigated production were considered separately and inputs of irrigation as infrastructure and those of blue water resources were taken distinctly. For non-crop economic activities, water was accounted for as a standalone factor of production by detailing current and future water use for other self-abstracting user classes (thermal power, industrial water, municipal water and livestock) and the underlying sectors supplied through water distribution networks.

Chapters 4 and 5 included the full specification of the RESCU-Water capabilities and data with all the water-related model features deemed to better integrate the freshwater demand and supply interactions into a multi-regional economy-wide framework. The relationship between income and population growth, and irrigation water requirements was captured in Chapter 6 through the consideration of three alternative socioeconomic development storylines combined with the expected technological change of land yield improvements. The impacts of climate change on water demand in irrigation were then determined in Chapter 7 by exploring alternative GHG emission pathways. The implications of increases in CO_2 concentrations were accounted for at multiple levels (yields, natural soil moisture and carbon fertilisation) enabling a more comprehensive conclusion regarding the major factors influencing future crop water productivity. In Chapter 8, future economy-wide water deficits relative to regional sustainability withdrawals thresholds were included through a further structuring of water demand outside crop production. The evolution of water uses under a 'no scarcity' baseline was explained through changes in scale, structure and water use efficiency of the largest non-crop water users. The analysis continued with an assessment of the economy-wide and food security impacts of demand-driven water deficits with an emphasis on water-scarce regions (India, South Asia, Middle East and Northern Africa). Different water management options under water scarcity were examined through the consideration of four alternative water allocation methods. The design of these methods stemmed from resource allocative efficiency principles on the one hand, and from social objectives regarding user prioritisation on the other.

9.2. Main findings

The main findings of the research gravitate around the three main research questions as outlined in the introduction of the thesis:

1. What is the future pressure on freshwater resources coming from irrigation water requirements with socioeconomic development?
2. How will mounting atmospheric concentrations of GHGs impact the water demand in irrigated crops?
3. What are the economy-wide and food security impacts of future demand-driven water scarcity under different climate change scenarios?

The answers to the first two questions cover the complex interactions between socioeconomic development, technological advancements and climate change incidence. The uncertainties regarding these drivers were addressed at two levels – *socioeconomic* through the consideration of multiple alternative futures (SSP1, SSP2 and SSP5), and *climate change* through the inclusion of alternative climatic responses (GCMs), greenhouse gas (GHG) concentrations scenarios (RCP2.6 and RCP8.5) and carbon fertilisation variants.

The analysis related to the third question built on the findings from the previous two by considering future regional water deficits in a world with and without climate change. The set of scenarios in a 'no climate change' world revealed the trade-offs between macroeconomic and food security impacts under different water management options. The addition of climate change across the two GHG concentration pathways enabled a more thorough understanding of food security implications of water scarcity and climate change occurring simultaneously and of the relative importance of the two phenomena.

9.2.1. Socioeconomic development impact on irrigation water requirements

The relationship between food demand and irrigation requirements is non-linear and requires a careful consideration of crop growing methods and water intensities across crop types and regions. The analysis showed that in a world not considering water scarcity constraints, though there is an important growth in irrigated crop production, irrigation water requirements grow at a much slower pace. These differences are explained by a more pronounced expansion in the production of water-efficient crops leading thus to an overall increase in irrigation water productivity at a regional level. Thus, for a crop output growth of 83%-101% obtained across the different SSPs considered, irrigation water requirements increase by only 8.5-11%.

The results show that the estimated expansion in irrigation water demand which occurred in the last century is unlikely to continue in the future, in line with the conclusions by the expert evaluation in Alexandratos & Bruinsma (2012). The water use dynamics in irrigation are explained through the interactions between a 'scale effect' determined by income and population growth and a 'substitution effect' induced by yield differences between crop types and between the rainfed and irrigated growing methods. These changes were determined at multiple levels – crop output, irrigation infrastructure use and irrigation water requirements.

In spite of this slow-down of global irrigation water requirements, the pressure over freshwater resources grows in most of the water-challenged regions. At the same time, there is a differentiated pressure coming from the eight crop classes considered in the model, as irrigated *wheat* and *veg&fruits* drive almost all increases globally; at regional level too, increases are determined by a small subset of crop types.

Socioeconomic development and yield improvements are equally important in driving irrigation water requirements. Income and population growth generally determine an increase in regional water demand, whilst differentiated yield changes can counter-balance this effect but can also further contribute towards expanding regional water use through rebound effects. China is the only irrigation-intensive country where the substitution effect induced by differentiated yield improvements is dominant, and leads to a change in the mix in the production of irrigated crops and consequently to an absolute reduction in regional demand for irrigation water. The importance of this effect in China is also confirmed through the IMPACT model calculating crop production and irrigation water demand using a "bottom-up" representation.

International trade increases with development and could represent an important source of water use savings through a growth in imports of water-intensive crops. However, given the current trade structure extended in the future, some water-stressed regions could expand their pressure due to significant exports of irrigated crops (South Asia virtual water net trade dominated by *veg&fruits*).

9.2.2. Climate change impacts on irrigation water requirements and crop water productivity

By 2050, anthropogenic climate change produces a visible impact on crop performance even in the low concentrations pathway RCP2.6. However, the results regarding crop output and regional water productivities are contrasting depending on whether the effects of CO_2 fertilisation (CF) over crop yields and crop water productivity are considered.

By taking into account only the changes in climatic conditions and natural soil moisture (i.e. no CF), production of most crops is adversely affected across regions notably on rainfed land. At the same time, the important drop in output of staple crops for both irrigated and rainfed varieties leads to a decrease in regional irrigation water requirements in spite of a lower regional irrigation water productivity compared to the baseline. Global changes in withdrawals relative to the SSP2 baseline are -1% and -5% for RCP 2.6 and RCP8.5 respectively. The decreases in water requirements are even more pronounced in the water-scarce areas of South Asia, India and Northern Africa. China is again the exception among the large irrigation-intensive regions, increasing water demand for crop production by over 10% compared to the baseline even in RCP2.6. A few other temperate regions (NE Asia, Northern Europe) also expand their irrigation water requirements due to the prevailing effect of water use intensification.

In terms of global food security, the 'no CF' climate change scenarios lead to significant alterations to the crop production mix notably in tropical regions due to the variance of crop-specific impacts. The crops most negatively affected are *rice* and *wheat*, followed by *oil seeds* and *veg&fruits*, whilst sugarcane output increases in many regions. Therefore, food production systems are altered to deliver less protein, fats and complex carbohydrates, and more simple sugars. This finding raises important questions, although not central to this thesis, on how diets will change and what the health implications will be of these alterations to crop availability.

The pronounced decline in output for the irrigated varieties of *wheat* and *rice* show that the extent of using irrigation as a climate change adaptation measure is limited for these staple crops. This lack of response is induced by the re-allocation of irrigation infrastructure and irrigable land to higher-value and more irrigation-efficient crop classes (*veg&fruits*, *fiber plants*). Thus, the important reduction in irrigated *wheat* production (-15% globally for RCP8.5 with a decrease in almost all regions) determines the single most important decrease in irrigation water requirements among all crops.

In the scenario variants which consider the CF effect, the negative impacts of climate change obtained previously are reversed. Crop production is therefore expanded even above the 'no climate change' baseline values for SSP2, whilst irrigation water requirements decrease even more compared with the 'no CF' scenarios – globally by -4% and -11% in RCP2.6 and RCP8.5 respectively. Also, CF appears to reduce the differences in crop output impacts between tropical and temperate regions.

Therefore, CF emerges as an important water-saving source which could lead to more water resources available to non-crop users, whilst supporting food production systems in meeting the growing crop demand driven by socioeconomic development. Nevertheless, these findings need to be treated with significant caution due to the uncertainty regarding the materialisation of the CF effect at large scale. The important interactions of CO_2 with ozone precursors which are also likely to be part of the future GHG mix could cancel the benefits of CF over crop performance along both the yield and crop water efficiency dimensions. More research would thus be welcome to cover the uncertainty induced by crop models in the CF representation and also by the importance of other factors mitigating this effect.

9.2.3. Economy-wide impacts of demand-driven water scarcity

Water deficits impacts under perfect climate change mitigation

The consideration of water deficits across multiple regions allowed for an assessment of the different water allocation regimes by taking into account region-specific economic structures and water use patterns. At the same time, the inclusion of international trade enabled the calculation of knock-on effects over water-abundant regions.

As expected, the highest macroeconomic impacts are obtained for a water management option with limited water mobility. The GDP deviation in 2050 from the baseline expansion is largest in the Middle East (-1.8% of real GDP), followed by South Asia (-1.6%), India (-0.4%) and Northern Africa (-0.02%). However, the obtained impacts are significantly lower than those determined by the only other similar assessment (World Bank 2016) where the decline in GDP could reach, for instance, 14% in the Middle East. These differences are explained by the lower water deficits induced by irrigation water demand as calculated through the RESCU-Water model using a "bottom-up" approach. At the same time, these lower impacts are also justified by the endogenous mechanisms for adaptation to water scarcity, namely (i) the variety substitution between rainfed and irrigated crops, and between thermal and non-thermal power and (ii) the substitution of water with other inputs in the production function of users supplied through distribution networks.

Therefore, although the annual GDP impacts are non-negligible ($130bn globally or 0.15% in global real GDP by 2050), these represent only a minor deviation from the considered growth pathways for the “middle-of-the-road” SSP2 storyline, even in water-scarce regions. Furthermore, the welfare effects determined using the Equivalent Variation measure are much lower ($23bn globally for the limited water mobility scenario). The re-allocation of production means to water-efficient activities explains these smaller impacts through a price deflation of some consumer goods and services.

Furthermore, the economy-wide impacts are considerably reduced when water is allocated based on relative user water productivities. The size of impacts depends, however, on multiple elements – the weight in GDP of water-intensive sectors, the relative size of water uses in these sectors, and the degree of flexibility in using water-related inputs in productive activities. Thus, low impacts were determined in diversified economies, i.e. with a small agricultural sector relative to the overall GDP, where water resources are allocated away from low-productivity activities (mainly irrigated crops). Therefore, regions with a high concentration of water uses in a small subset of crop types (India with *rice* and *wheat*, Northern Africa with *other crops*) see low negative implications at a macroeconomic level.

The adverse impacts could further be reduced through international trade by extending the imports of virtual water. However, the role of trade is dependent on the baseline import dependency of water-intensive goods and on trade barriers. Through the Armington specification used in the RESCU-Water model, only the Middle East sees an important increase in virtual water imports, equivalent to 7% of global virtual water trade obtained in the ‘no scarcity’ baseline and mostly related to trade of crops. The other three regions have only minor changes in virtual water trade due to a low initial import dependency in the case of water-intensive commodities.

Interestingly, due to the interaction of water inputs with other factors of production, the lowest GDP impacts are not obtained using the water allocation regime purely based on differences in water productivity (FA method). By further constraining water availability to crop sectors which are also labour and capital intensive, as done in the AL allocation method, the economy-wide factor productivity is improved leading to better GDP outcomes. Therefore, applying the allocative efficiency principles for water also needs to account for the differences between sectors regarding other endowment input intensity.

From a sectoral perspective, the incidence of demand-driven water scarcity over output is highest for economic activities with a limited flexibility over water input levels and with a low water productivity. Hence the reduction in output is largest for crops with knock-on effects over the underlying food processing sector. At the same time, thermal power production, with a comparatively higher water efficiency, is also reduced through the switch to non-thermal power. For other indirect water users (supplied through water distribution networks), the model included a reduced degree of substitution away from water inputs in supplied industrial activities (primary energy, construction, chemicals, paper and manufacturing) and more flexibility for municipal users (services). With this specification, the typical output drop in water-intensive industries for the limited water mobility scenario is 2% in the Middle East, 1% in India and 3.5% in South Asia. These impacts are, however, sensitive to the elasticity of substitution between the supplied water inputs (industrial water) and all other inputs, as shown in the sensitivity analysis in Chapter 8. Therefore the value of this elasticity is important both in these sectors and for the entire economy as most of the GDP deviations in diversified economies are derived from changes in water-constrained industrial activities.

Food security measured as a function of crop availability and crop prices is visibly affected across all water allocation methods analysed but to different degrees depending on how crop production is prioritised. The smallest impacts are obtained when the water mobility is limited (LM) or when a volume of water resources is reserved for use in irrigation (MF). In the LM case, there is a moderate however more uniform reduction in the irrigated output across all crop classes. A re-allocation of water across crop types isolated from that across non-crop users (MF) enables a re-distribution of resources to water-efficient crops with an impact on the crop production mix. However, this method prevents more water volumes from being re-directed from water-intensive crops to sectors outside agriculture with much higher water productivities.

As expected, the highest food security impacts are obtained in a water management regime treating crops as the lowest priority users (AL). Most global economic models with a focus on water adopt this low-priority assumption for crop sectors. However, the impacts obtained in this thesis also include the increased water use of non-crop users leading to larger constraints regarding the water availability for crop production. The drop in output obtained for staple crops in 2050 was of the order of a fifth of the baseline production in India, South Asia and the Middle East, with impacts in Northern Africa much attenuated by the concentration of water demand reductions in the non-food crops. The prices of *wheat* and *rice* thus increase by more than 15% in India and South Asia and more than 10% in the Middle East. At the same time, not all crop production is reduced, but some crop classes can even benefit from more water resources allocated when including water productivity considerations (*veg&fruits* and *oil seeds* in India, South Asia and Northern Africa).

Climate change and demand-driven water scarcity

The addition of climate change incidence by considering the alterations to climatic conditions and natural soil moisture (excluding the effect of CF) leads to further adverse impacts on food security. The negative impacts on crop output also include the more water-efficient crop classes of *veg&fruits* and *oil seeds*.

Demand-driven water scarcity has a dominant effect on crop production even in RCP2.6. However, the high climate change RCP8.5 scenario results in a doubling of negative impacts obtained under ‘no climate change’ for *rice* and *wheat* across all water-scarce regions with negative effects on almost all other crop classes. Furthermore, the water savings obtained previously through the contraction in crop output under climate change alone are much lower than the required reduction in irrigation water withdrawal volumes imposed by the sustainability thresholds. Thus, changes in overall withdrawals for irrigation induced by climate change are negligible. Therefore, climate change in conditions of water scarcity has an additional negative effect to crop output more from a yield reduction perspective than from that of regional water productivity losses.

The two water allocation regimes considered for the climate change scenarios (FA and AL) do not produce significant differences in terms of crop output. Nevertheless, the effects of climate change on crop water intensity in the four water-scarce regions lead to slightly higher impacts when agriculture is treated as the lowest priority user (AL) to reflect the fact that yield changes may further increase the differences in water productivity between crop and non-crop sectors.

9.3. Policy implications

The above findings lead to important conclusions for policymaking related to water management, food security and climate change adaptation. First, the macroeconomic impacts of water scarcity depend on how the water resource base is allocated across the economy. The less reliant an economy is on agriculture, the greater the economy-wide impact differences across allocation regimes will be. Second, although the growth in irrigation water demand will slow down in the next decades, any water allocation regime based on water productivity considerations will have a high impact on crop production, especially on staple crops, and implicitly on food security. Third, globally, irrigation may not be a viable adaptation measure against the changes in mean climatic conditions for the basic food crops (*wheat* and *rice*) due to their high water intensities. Furthermore, the capacity of crop systems, in general, to switch to irrigated production will be constrained by water scarcity driven by a growing demand from non-crop sectors.

The alternative water allocation methods considered show that, from a water management perspective, any decision regarding user prioritisation would imply a trade-off between macroeconomic and food security impacts. These trade-offs introduce an important nuance to the conclusions of other analyses on the economy-wide effects of demand-driven water scarcity (e.g. World Bank 2016) that made a case for an allocation based on relative water productivities of users. A pure application of the allocative efficiency principle would lead to important volumes of water moved away from crop production and could thus significantly damage the food security prospects of water-scarce regions. Therefore, a more complex allocation system could be adopted to offer some protection to food systems through improved water availability for agriculture.

The implementation of a water allocation regime may be difficult due to several current factors – the lack of assignment of water rights, the non-existence of a conveyance infrastructure enabling water mobility across large geographical areas, the sub-optimal water pricing regimes where even the economic cost of supplying water is rarely covered. However, without a direct policy intervention in this regard both the macroeconomic and food availability impacts could be higher due to increased distortions in water allocation induced by differences in water accessibility of users (which user can access water resources first), and due to groundwater depletion in the long-run. Therefore, in the absence of a specific set of measures leading to a proper valuation of water to reflect its scarcity, the use of water will continue to be prone to inefficiencies and wastage.

For food security objectives, water allocation mechanisms could also be complemented by better water management on the demand-side leading to a reduction in water requirements for irrigation. The evolution of water demand in irrigation will depend on the expansion of crop demand, the improvements in irrigation efficiency, and also on how the intensity of beneficial crop water will evolve with the technological advances for yields.

Crop demand could be influenced by addressing the issue of food waste applicable equally to industrialised and developing regions. For developing countries, food waste mostly occurs currently at the farm and food distribution levels and less at the consumer level. Thus, as water-scarce regions continued to develop, it will be important to address the issue of storage food spoilage, but also to counter the similar patterns of food waste observed in developed regions at the household level. The way in which diets will potentially evolve, through more meat intake as regions develop, will also play an important role in crop demand for feedstock.

The large inefficiencies in irrigation could be improved through investment in better conveyance and field application technologies. An increase in efficiency rates of only 5% from current levels would be equivalent of 30% of water deficits in 2050 in India, 31% in South Asia, 17% in the Middle East and more than the total deficits in Northern Africa. This level of efficiency improvements could be obtained through direct policy intervention as half of irrigation water losses occur at the conveyance stage where infrastructure investments are dependent on government action. At the same time, better water pricing to reflect the cost of supply and the removal of energy subsidies affecting groundwater pumping could also improve the water use efficiency of distributed uses. For instance, Jägermeyr et al. (2015) indicate that a change of field application from 'surface' to 'sprinkler' irrigation would reduce non-beneficial water use by more than 50% across world river basins. Furthermore, given the level of concentration in water uses across crops, irrigation efficiency could also be targeted towards the major irrigated crops with a low water productivity (notably *wheat* and *rice*) to improve their abilities to cope with water scarcity.

Higher crop yields may not imply the same improvements in water productivity. Therefore the growth in yields would need to take advantage of the yield gaps induced by water-fertiliser imbalances (McKinsey 2009). A further increase in crop water productivity with yield growth could be obtained through the adoption of drought-resistant varieties. However, the implied gene modifications raise important public acceptance issues.

These measures could reduce the tension between the food and water SDGs set for 2030 by adopting a longer-term view. The capacity to meet SDG2 related to ending hunger, achieving food security and improving nutrition would be significantly affected by water scarcity and climate change. At the same time, SDG6.4 to increase water-use efficiency and to ensure sustainable withdrawals could be at risk without addressing the issue of water use expansion in irrigation. Therefore improving the overall water footprint of food systems could be the middle ground in meeting these goals.

International trade would also be an important lever in this regard by shifting production of water-intensive commodities in water-abundant regions where rainfall is high. Regions allowing increases in imports of crops improve their food availability and also benefit from lower price increases determined by water scarcity. These effects are obtained in cases in which production self-sufficiency is not a priority and thus where import dependency is significant. However, moving production abroad could contribute to undesirable land-use change with deforestation and loss of biodiversity especially in tropical regions (Central Africa, Brazil, SE Asia). At the same time, the distributional effects of lowering trade barriers need to be accounted for as many households in the water-scarce regions considered may still rely on agriculture for their livelihoods in the time horizon to 2050 – South Asia is a case in point where food production continues to be an important sector in the economy.

Water demand reduction in non-crop sectors would also be possible through two channels – increases in water use efficiency in industrial and municipal activities but also through re-structuring the economy around water-efficient sectors. On the one hand, the efficiency improvement costs could prove however much higher than those for irrigation (see McKinsey 2009 for the cost curve for India). On the other, water use reduction through economic re-structuring could imply changing the technological routes of water-intensive activities (e.g. thermal and non-thermal power production) or moving away from water-inefficient activities altogether. These structural shifts were captured in the RESCU-Water model simulations. However, they remained limited outside food and thermal power production, with a reduction in output of up to 3.5% for the other water-using activities.

Regarding climate change, the mitigation of GHG emissions should be preferred to adaptation. Even with low GHG concentrations, food security is affected especially in tropical regions through a reduction in crop availability leading to imbalances in the supply of macro-nutrients, and through an intensification of irrigation water use. Also, counting on carbon fertilisation as a means to boost crop production and reduce irrigation water requirements represents a path with many uncertainties, and it is thus questionable whether relying on the potential water savings from this effect is sensible.

At the same time, important water demand reductions for thermal cooling could come through policies aimed at climate change mitigation as this would imply the adoption of renewable energy technologies such as wind power and solar PV which have a much lower water intensity. It could, therefore, be expected that due to constraints in withdrawals by thermal power plants, a transition towards green technologies could be encouraged by water scarcity. However, an underexplored area in this thesis and in general refers to the impact over water availability from an expansion in hydropower production.

From a climate change adaptation angle, one proposed measure is to ensure more water storage and improve access to irrigation water (Porter et al. 2014) to compensate for the potential drought effects on rainfed land. With a growing demand from non-crop sectors, it is arguable whether these solutions in water-scarce regions will be effective given the potential reduction in the availability of water for irrigation. Furthermore, with climate change, the relative water productivities of water-intensive crops (*wheat* and *rice*) may continue to decline further limiting their capacity to compete for scarce water resources and thus to use irrigation as an adaptive measure.

9.4. Thesis contribution

The findings in this thesis bring insights into water management options at a time of increased concerns over the economy-wide risks of future water scarcity. The range of contributions is broad and consists of *methodological advances* in assessing the impacts of demand-driven water scarcity at a global level, in the *re-shifting of research focus* in the area of economic modelling towards the macro-economic and sectoral impacts of water deficits and in the *production of new knowledge* by exploring impacts of water allocation regimes and the multiple uncertainties of the demand side drivers of water scarcity.

Methodological advances

The development of the RESCU-Water model consisted of a thorough integration of model capabilities required for the global impact assessment of future water deficits. These capabilities cover (1) a detailed representations of water uses across sectors under different pathways of socioeconomic development and climate change, (2) the consideration of alternative water allocation mechanisms for water-scarce regions, (3) the measurement of impacts at a macroeconomic level (GDP), but also at a household (welfare) and sector-specific level (output) and (4) the consideration of regionalised water scarcity effects on water-abundant regions through the inclusion of bilateral international trade flows. These elements have previously been implemented individually in the different water-focused economic models. However, no one instance has so far integrated them all until now. Furthermore, RESCU-Water included modelling advances of the state-of-the-art across all four aspects.

For the water use representation across sectors (1), the model comprises an advanced specification of sectoral water inputs with a focus on irrigation water requirements for which a "bottom-up" approach was employed. Water was included as a distinct factor of production by distinguishing between self-abstracting sectors and the supplied user. The distinction between the five self-supplied activities was done through a separate accounting of water uses that was facilitated by the recent advancements in water use estimations notably for irrigated crops and thermal power plants. In addition to the supply costs, the scarcity value of water was also included through payments for the use of water endowments in regions with water deficits. Next, the changes of the GTAP database through the splitting of crop sectors into rainfed and irrigated comprised an improvement in the irrigation valuation methods used in other models.

The addition of water factor inputs next to irrigation also allowed for a reconsideration of the water scarcity scenarios used in previous assessments overlooking differences in crop water intensities and where water demand was assumed to be capped by constraining the regional use of irrigation equipment. Finally, the use of a macroeconomic framework allowed for a consistent consideration of the relationship between socioeconomic development as specified by the new SSP framework and future water demand detailed by user category. Furthermore, water demand evolution was explained through the integration of coherent data (by using the same socioeconomic assumptions) from specialised models (the LPJmL crop model and the TIAM-UCL energy systems model) and by considering different sources of uncertainty influencing this demand.

The water allocation mechanisms implemented (2) have a broader coverage of possible water scarcity impacts compared to previous studies. The widely-used allocation principle treating crops as the lowest priority user (AL) was thus complemented by water regimes with limited water mobility (LM), those aiming for water allocative efficiency (FA) or those aimed to protect crop systems from competition coming from the other sectors (MF). The detailed water use representation across sectors also allowed for endogenous and sector-specific adaptation mechanisms to water scarcity, in contrast to the prescriptive sectoral water allocation used recently in World Bank (2016).

Regarding the impact measurement of water scarcity (3), the level of disaggregation used in the RESCU-Water model also enabled more nuanced conclusions regarding the incidence of water scarcity. The differences in outcomes across crop and non-crop sectors allowed for an understanding of the trade-offs between the macroeconomic and the food security impacts. Also, the disaggregation of the power sector into thermal and non-thermal production captured the adaptation mechanism by shifting production to water-efficient technological options.

The inclusion of international trade (4) was facilitated by the use of a global economic framework and the use of the GTAP database comprising bilateral trade data. At the same time, water-abundant regions were enabled to use their competitive advantage. In these regions, the expansion of withdrawals was implemented such that the production of water-intensive commodities and the regional water demand could grow as a function of changes in exports to water-scarce regions.

Research focus

The economy-wide impacts of water deficits have not been central to research efforts in the past decade, and the models used before (GTAP-W1 and FARM) are by now dated and do not align with the state-of-the-art in water accounting and water use representation. All of the newer model development (GTAP-W2, GTAP-BIO-W, EPPA, ICES-W) has focused on the water scarcity incidence on crop production systems. Furthermore, water scarcity was largely assessed from a supply-side perspective by considering alterations to run-off coming from climate change. It was only recently that non-crop water uses were included in an economic modelling framework (Roson & Damania 2016) to measure the macroeconomic impacts of demand-driven water scarcity. Therefore, the assessment in Chapter 8 of this thesis contributes towards this shift of the research agenda towards the economy-wide implications of water deficits coming from the evolution of global water demand. As mentioned, through the use of a water-specialised CGE model with a great level of sectoral detail, the discussion of water allocation choices can be expanded to include food security considerations in addition to aggregate GDP implications.

Knowledge expansion

The answers to the research questions bring new knowledge regarding future water demand and the impacts of different water allocation regimes. The “bottom-up” representation of crop systems enabled the calculation of changes in withdrawals for irrigated crops. By taking advantage of the economy-wide view over resource allocation not captured in partial equilibrium models, future irrigation water requirements were calculated for the first time using consistent assumptions regarding the availability of means of production throughout production processes. Furthermore, the relative importance of socioeconomic factors and that of technological change was assessed in relation to future pressure over the water resource base coming from irrigation withdrawals. Thus, as argued for in Wada et al. (2016), the model results contribute towards establishing a water demand baseline as a requirement for inter-model comparison of water scarcity scenarios.

The unconstrained water demand in irrigation was also considered through a better representation of climate change impacts over crop performance. Previously, the effects of climate change were limited to yield alterations coming from changes in climatic conditions and CF. In this thesis, climate change implications for irrigation water use were determined by integrating changes in crop water productivities coming from CF and alterations to natural soil moisture. Furthermore, the model simulations were determined by accounting for the uncertainty of climate change response through the use of alternative climate modelling outputs.

Therefore, water use dynamics of the largest water user were explained through an integration of socioeconomic development, technological advancement and climate change incidence. This type of analysis was explored for cropland in the AgMIP model inter-comparison work. However, the coverage of water use was generally done to a much lesser extent in economic modelling.

The water scarcity analysis of economic impacts revealed the importance of considering alternative water allocation regimes across the GDP and food security dimensions. It also showed that promoting water allocative efficiency needs to be considered in conjunction with the sectoral intensity of other factors of production (labour and capital). Another novelty was the simultaneous simulation of climate change and water scarcity impacts indicating a significant reduction in the availability of staple crops, and that the role of irrigation as an adaptation measure to climate change will be limited by demand-driven water scarcity.

9.5. Limitations and uncertainties

Some limitations and uncertainties need to be factored in when considering the findings of this thesis. Whilst most of these have been addressed through scenario variation and sensitivity analyses, a few remain and are largely related to the projections of regional water uses and to the sustainability thresholds introduced in the water scarcity scenarios.

For the regional water calculation, the water withdrawals for hydropower plants have not been accounted for. Hence, the water intensities of the non-thermal power sector are underestimated. The reason for not including this component is given by the relevance for dams of water consumption through evaporation and not that of in-stream withdrawals. Water demand in this thesis has been considered in relation to withdrawals, making thus the water consumption for hydropower incompatible with the accounting conventions employed here. Furthermore, the projections of global water consumption for hydropower would be difficult as these would depend on the size, form and climatic conditions of the implied dam infrastructure. Thus, the water demand in this area could represent a standalone research topic.

Regarding the water uses that were included, irrigation water requirements were influenced by the allocation of irrigation as infrastructure across crop types, but also on the overall irrigation supply which was included through a logistic functional form. The costs of expanding irrigation were not included and should be the subject of future work by considering the implications for capital investment and labour use. The inclusion of these additional costs could imply a lower expansion of irrigated crop production and implicitly lower irrigation withdrawal levels.

For other users (industrial and municipal), water demand was calculated by considering the scale, structure and efficiency of water-using activities. Whilst the relationships employed build on the previous work undertaken in biophysical modelling frameworks, these were not empirically tested and thus could be improved. Nevertheless, there are large variations even across projections using statistical analysis and that use the same set of assumptions as in the WFaS initiative (Wada et al. 2016). At the same time, the RESCU-Water modelling framework was constructed in such a way that the dynamic calibration of sectoral water intensities could be implemented using any alternative water demand projections for non-crop self-abstracting sectors.

The withdrawals thresholds used to indicate water scarcity were determined relative to the regional TRWR values and the current state of river basin overexploitation across regions. Furthermore, in the case of the Middle East, no water provisions were made for the environment for the ease of comparing water allocation regimes. These thresholds could also be re-assessed through the use of additional hydrological information taking into account more specific water withdrawals constraints and spatially-detailed environmental flow requirements. This would be particularly important for China for which the projected withdrawal levels are getting close to the high-stress threshold (40% of TRWR). However, there are large water availability discrepancies within the country with the result that some regions are at risk of water supply disruptions (HSBC 2012; OECD 2017).

Hence, the water deficits determined include some limitations on both the demand (regional water demand) and supply (withdrawal thresholds) sides. However, whilst the size of these deficits influence the GDP and sectoral impacts, the conclusions regarding the differences in water allocation regimes for GDP and food security trade-offs, international trade and those related to the interlinkages between water scarcity and climate change remain valid. As most of the water demand reduction is obtained from irrigation due to the lower water productivities of crops relative to the other sectors, crop systems remain the economic area most exposed to water scarcity.

9.6. Further research

Through the advanced specification of water use across sectors, the RESCU-Water model represents a versatile tool for analysing economy-wide issues of water scarcity and water management. In this thesis, the model was used to assess the impacts of water deficits coming from an expansion in water demand across regions and economic activities. All the same, the model applications could be expanded to research areas connected to water management, food security and climate change adaptation. Thus, some of the solutions presented in the policy implications section could be further explored using this framework.

Whilst the results presented in this thesis refer to regional aggregates capturing a generalised state of water scarcity in some extended geographical areas, further work could be dedicated to the assessment of water use constraints for economic activity in water scarcity hotspots e.g. Western Great Planes in the USA, Northern China. Hydrological modelling informed by advanced spatial data regarding water uses could help quantify the restrictions of localised scarcity for parts of specific economic activities e.g. agriculture, thermal power in certain river basin or agro-ecological zones. This approach has been taken in country-level analyses, however, for global assessments, current practices using downscaling techniques for industrial and municipal uses could prove to produce unreliable results. Therefore, improvements in global data collection regarding the spatial distribution of water demand would be beneficial. At the same time, a complementary approach would be changing the model regional disaggregation to focus on particular countries which were aggregated in this thesis in wider geographical areas e.g. South Africa. A structuring of economic data around water scarce areas whilst reducing the level of geographical detail for water-abundant regions could also help reduce the computational challenges implied by disaggregated global CGE models.

On the water management side, alternative water allocation regimes such as increased water availability for crop production could be implemented in conjunction with policy intervention related to improving water efficiency in irrigation in general or for particular crop types. Also, more water allocation regimes could be tested for identifying the water management option producing the best climate change adaptation outcomes for food security, or for minimising the overall negative welfare impacts.

The changes in the crop production mix could also lead to health issues. For instance, India is currently dealing with a spike in diabetes incidence due to changes in lifestyle coming from socioeconomic development. A larger relative availability of sugars as obtained in the model results could be a further stimulus to this problem and some specific policy intervention may be required to counter this issue (e.g. a sugar tax). Again, the modelling framework developed could answer important questions regarding the water pressure and food security impacts of these changes.

Given the significant impacts on crop systems, the calculation of household distributional effects of implementing specific water allocation regimes would be desirable. The decreases in crop production would affect farm level revenues, whilst the introduction of water rights could offset some of this income reduction as farmers would be compensated for giving up the use of irrigation water. This revenue recycling was included in the RESCU-Water simulations. However, the inclusion of more detail regarding household groups in assigning these rights could enable a more advanced calculation of the impacts of water scarcity on low-income and farming households. This task has been accomplished to some extent in country-level models. Nevertheless, the distributional impacts in global assessments are still conducted using separate microsimulation modules as households continue to be aggregated in one income group in global economic databases such as GTAP.

Climate policy is another area with important implications for water scarcity. The model linking with TIAM-UCL could be extended to cover the changes in the energy mix for different climate change pledges and the implied evolution of water requirements for energy production. The analysis of climate change incidence over water demand could thus include non-crop sectors. One area affected by increases in temperature is thermal power generation which may intensify withdrawals for cooling purposes. On the water supply side, water availability changes due to climate-induced alterations to run-off could be included through the use of global hydrological modelling data. Therefore, through a better integration of the food-water-energy-climate nexus, the co-benefits of reducing GHG emissions over the size water of deficits and the associated economic and food security impacts could be revealed.

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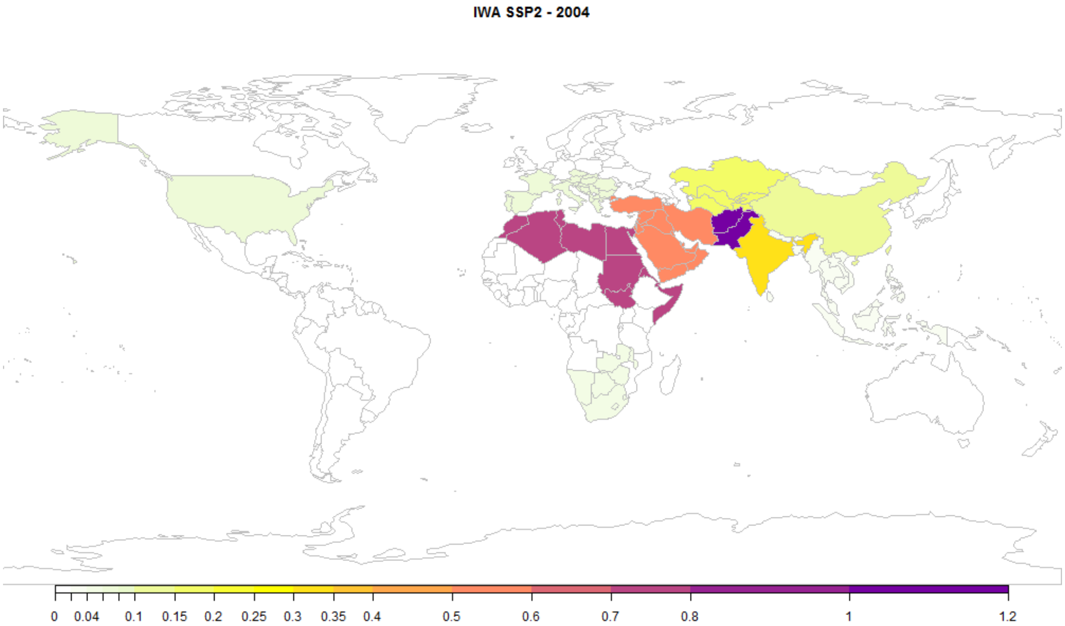
Annex A: Chapter 6 – Projecting irrigation water requirements across multiple socioeconomic development futures



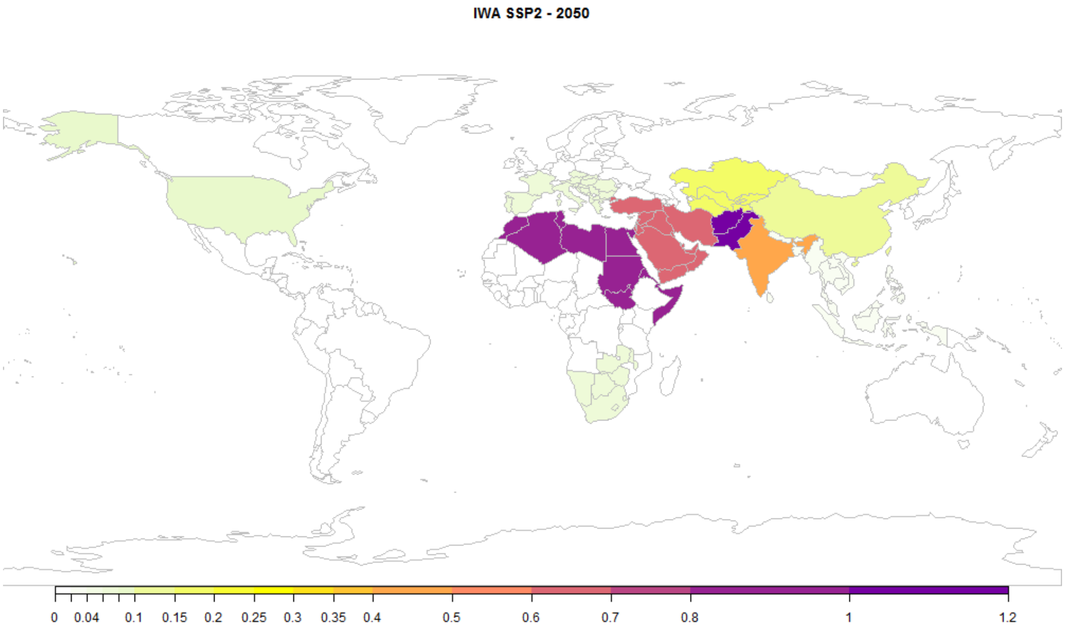


Figure A1 – IWA heat maps 2004 and 2050

Table A1 – Rainfed and irrigated annual yield changes in the RESCU-Water 2004-2050 baseline

RESCU-Water region	Wheat			Rice			Other grains			Veg&fruits		
	Irrigated	Rainfed	*Δ*	Irrigated	Rainfed	*Δ*	Irrigated	Rainfed	*Δ*	Irrigated	Rainfed	*Δ*
Australia&NZ	0.13%	0.42%	*-0.29%*	-0.09%	-0.45%	*0.37%*	0.57%	0.58%	*-0.01%*	1.37%	0.95%	*0.42%*
Brazil	1.53%	1.46%	*0.07%*	0.65%	0.65%	*0.00%*	1.68%	1.18%	*0.50%*	1.98%	1.01%	*0.97%*
Sahel	1.51%	1.66%	*-0.16%*	0.91%	1.03%	*-0.11%*	2.10%	1.27%	*0.83%*	1.03%	0.86%	*0.17%*
Central Africa	0.62%	2.56%	*-1.94%*	1.57%	1.16%	*0.41%*	1.56%	1.56%	*-0.01%*	1.99%	0.97%	*1.02%*
China	0.43%	0.53%	*-0.10%*	0.36%	0.65%	*-0.29%*	0.95%	1.20%	*-0.24%*	0.87%	0.01%	*0.85%*
Eurasia	1.73%	1.60%	*0.13%*	1.89%	1.63%	*0.26%*	2.44%	1.95%	*0.49%*	1.09%	1.00%	*0.09%*
India	0.79%	0.63%	*0.16%*	1.05%	0.54%	*0.51%*	1.33%	2.02%	*-0.68%*	1.02%	0.79%	*0.23%*
Middle East	1.61%	1.23%	*0.38%*	1.11%	1.14%	*-0.03%*	1.77%	0.94%	*0.83%*	1.17%	0.60%	*0.57%*
Northern Africa	0.35%	1.91%	*-1.56%*	0.29%	0.36%	*-0.06%*	-0.14%	1.04%	*-1.17%*	1.43%	1.29%	*0.14%*
Northeast Asia	0.48%	0.50%	*-0.01%*	0.19%	0.12%	*0.07%*	0.61%	0.51%	*0.11%*	0.94%	0.76%	*0.19%*
Northern Europe	0.41%	0.57%	*-0.16%*	0.72%	0.72%	*0.00%*	0.89%	0.91%	*-0.02%*	1.15%	0.65%	*0.50%*
North Latin Am	0.06%	0.82%	*-0.76%*	0.22%	0.35%	*-0.13%*	0.95%	1.09%	*-0.14%*	0.98%	0.44%	*0.53%*
Canada	1.42%	1.80%	*-0.37%*	1.24%	1.24%	*0.00%*	1.37%	1.59%	*-0.22%*	1.80%	0.96%	*0.84%*
Southern Africa	0.69%	1.27%	*-0.58%*	0.88%	0.41%	*0.47%*	1.28%	0.93%	*0.35%*	1.19%	0.59%	*0.60%*
South Asia	0.86%	1.57%	*-0.71%*	0.62%	0.67%	*-0.05%*	1.56%	1.05%	*0.50%*	1.06%	1.33%	*-0.27%*
Southeast Asia	1.51%	2.45%	*-0.94%*	0.65%	0.51%	*0.15%*	0.90%	0.98%	*-0.08%*	1.40%	0.98%	*0.42%*
Southern Europe	1.44%	1.01%	*0.43%*	1.08%	0.85%	*0.22%*	0.27%	0.82%	*-0.55%*	1.28%	0.45%	*0.82%*
South Latin Am	0.55%	0.88%	*-0.33%*	0.51%	0.68%	*-0.18%*	1.05%	1.10%	*-0.05%*	0.86%	0.98%	*-0.12%*
USA	1.29%	1.25%	*0.04%*	1.14%	0.89%	*0.26%*	0.84%	0.99%	*-0.15%*	1.20%	0.87%	*0.33%*

Table A1 – Rainfed and irrigated annual yield changes in the RESCU-Water 2004-2050 baseline (continued)

RESCU-Water region	Fiber plants			Cane&beet			Oil seeds			Other crops		
	Irrigated	Rainfed	*Δ*	Irrigated	Rainfed	*Δ*	Irrigated	Rainfed	*Δ*	Irrigated	Rainfed	*Δ*
Australia&NZ	2.10%	1.93%	*0.17%*	0.47%	0.40%	*0.08%*	0.68%	0.46%	*0.22%*	0.86%	0.55%	*0.31%*
Brazil	1.92%	1.91%	*0.02%*	0.66%	1.14%	*-0.48%*	1.69%	0.84%	*0.85%*	2.03%	0.90%	*1.13%*
Sahel	2.12%	0.80%	*1.32%*	1.22%	1.01%	*0.21%*	0.67%	1.31%	*-0.64%*	1.42%	-0.09%	*1.51%*
Central Africa	0.98%	1.08%	*-0.10%*	0.32%	0.64%	*-0.32%*	-0.65%	1.08%	*-1.73%*	1.35%	0.62%	*0.73%*
China	0.20%	1.01%	*-0.81%*	1.38%	0.76%	*0.61%*	0.50%	0.62%	*-0.12%*	-0.04%	0.91%	*-0.95%*
Eurasia	1.03%	1.04%	*-0.01%*	1.82%	1.82%	*0.00%*	2.98%	1.32%	*1.66%*	0.35%	-0.13%	*0.48%*
India	1.78%	1.86%	*-0.09%*	0.08%	0.02%	*0.06%*	1.54%	0.98%	*0.56%*	0.25%	0.09%	*0.16%*
Middle East	1.79%	1.66%	*0.13%*	1.09%	0.93%	*0.16%*	1.79%	0.94%	*0.85%*	1.07%	-0.02%	*1.09%*
Northern Africa	0.98%	0.89%	*0.09%*	0.59%	0.40%	*0.18%*	1.21%	1.25%	*-0.05%*	0.41%	0.76%	*-0.35%*
Northeast Asia	0.47%	0.47%	*0.00%*	0.47%	0.52%	*-0.04%*	0.20%	0.65%	*-0.45%*	0.08%	0.56%	*-0.49%*
Northern Europe	0.72%	0.72%	*0.00%*	0.54%	0.60%	*-0.06%*	0.72%	0.36%	*0.36%*	1.17%	0.71%	*0.47%*
North Latin Am	1.46%	1.14%	*0.33%*	1.03%	1.19%	*-0.15%*	0.59%	0.15%	*0.45%*	0.07%	-0.12%	*0.19%*
Canada	1.24%	1.24%	*0.00%*	1.24%	1.00%	*0.25%*	1.24%	0.26%	*0.98%*	1.36%	0.88%	*0.48%*
Southern Africa	2.25%	1.53%	*0.72%*	0.57%	0.53%	*0.04%*	0.37%	0.44%	*-0.07%*	1.62%	1.01%	*0.61%*
South Asia	0.95%	0.61%	*0.34%*	1.19%	1.22%	*-0.03%*	1.51%	1.82%	*-0.31%*	0.17%	-0.16%	*0.32%*
Southeast Asia	1.12%	0.99%	*0.14%*	0.59%	0.59%	*0.00%*	0.53%	0.30%	*0.23%*	1.57%	0.08%	*1.48%*
Southern Europe	0.42%	0.30%	*0.12%*	0.96%	0.83%	*0.12%*	0.93%	0.85%	*0.08%*	1.99%	0.75%	*1.23%*
South Latin Am	2.06%	1.65%	*0.41%*	0.98%	0.92%	*0.06%*	1.29%	0.30%	*0.99%*	0.14%	0.59%	*-0.45%*
USA	1.79%	1.84%	*-0.05%*	0.74%	0.64%	*0.09%*	1.78%	1.19%	*0.59%*	1.48%	1.20%	*0.29%*

Table A2 – RESCU-Water crop price - average annual growth rate in SSP2

	overall	wheat	rice	other grains	veg& fruits	plant fibres	cane& beet	oil seeds	other crops
Aus&NZ	**0.8%**	0.9%	0.9%	0.6%	0.7%	0.3%	1.0%	1.2%	1.1%
Brazil	**0.7%**	0.7%	0.7%	0.6%	0.7%	0.5%	0.7%	0.7%	0.6%
Sahel	**1.2%**	1.0%	1.4%	1.0%	1.4%	1.3%	1.7%	1.5%	1.4%
Central Africa	**2.1%**	1.4%	2.2%	2.0%	2.2%	1.8%	2.4%	2.6%	2.2%
Central Asia	**1.4%**	1.1%	0.9%	1.3%	1.5%	1.5%	1.3%	1.4%	2.0%
China	**1.9%**	1.6%	2.1%	1.5%	2.1%	1.4%	1.7%	1.7%	1.9%
Eurasia	**0.4%**	0.4%	0.4%	0.3%	0.5%	0.4%	0.3%	0.4%	0.7%
India	**2.8%**	2.0%	3.0%	2.0%	3.0%	2.1%	3.3%	3.0%	3.2%
Middle East	**0.7%**	0.7%	1.0%	0.6%	0.8%	0.4%	0.7%	0.8%	1.1%
Northern Africa	**0.8%**	0.7%	1.1%	0.8%	0.7%	0.6%	0.9%	0.9%	1.1%
NE Asia	**0.2%**	0.3%	0.2%	0.3%	0.2%	0.2%	0.2%	0.5%	0.3%
Northern Europe	**0.4%**	0.4%	0.7%	0.3%	0.4%	0.4%	0.4%	0.3%	0.5%
Northern Latin Am	**0.7%**	0.5%	0.7%	0.6%	0.7%	0.3%	0.6%	0.7%	1.0%
Canada	**0.3%**	0.2%	0.5%	0.2%	0.3%	0.2%	0.4%	0.4%	0.4%
Southern Africa	**0.6%**	0.6%	0.9%	0.6%	0.6%	0.5%	0.6%	1.0%	0.9%
South Asia	**1.3%**	1.4%	1.4%	1.1%	1.2%	1.2%	1.2%	1.1%	1.9%
SE Asia	**1.8%**	1.4%	2.0%	1.8%	1.8%	1.3%	1.9%	1.6%	2.1%
Southern Europe	**0.4%**	0.3%	0.5%	0.4%	0.5%	0.5%	0.4%	0.4%	0.4%
Southern Latin Am	**0.9%**	0.8%	0.8%	0.7%	0.9%	0.4%	0.7%	1.0%	1.1%
USA	**0.4%**	0.3%	0.3%	0.3%	0.4%	0.2%	0.5%	0.3%	0.4%
World	***1.3%***	***1.0%***	***1.7%***	***1.1%***	***1.5%***	***1.2%***	***1.1%***	***1.3%***	***1.0%***

Note: Crop prices in the RESCU-Water model grow at a rate of 1.3% p.a. globally, with significant increases in high economic growth regions (China, India, Central Africa). The AgMIP models in Valin et al. (2014) equally show a general agreement of a long-term trend of increasing prices for agricultural products. However, the price increases in RESCU-Water are larger than the range of changes obtained in the model inter-comparison exercise. This difference could come from the demand system choice and calibration as the AgMIP models use price and income elasticities for food commodities other than those based on GTAP. Another determinant could be the land use specification with the AgMIP models being more advanced in capturing land conversion possibilities.

Annex B: Chapter 7 – The impacts of higher CO_2 concentrations on global crop production and irrigation water requirements

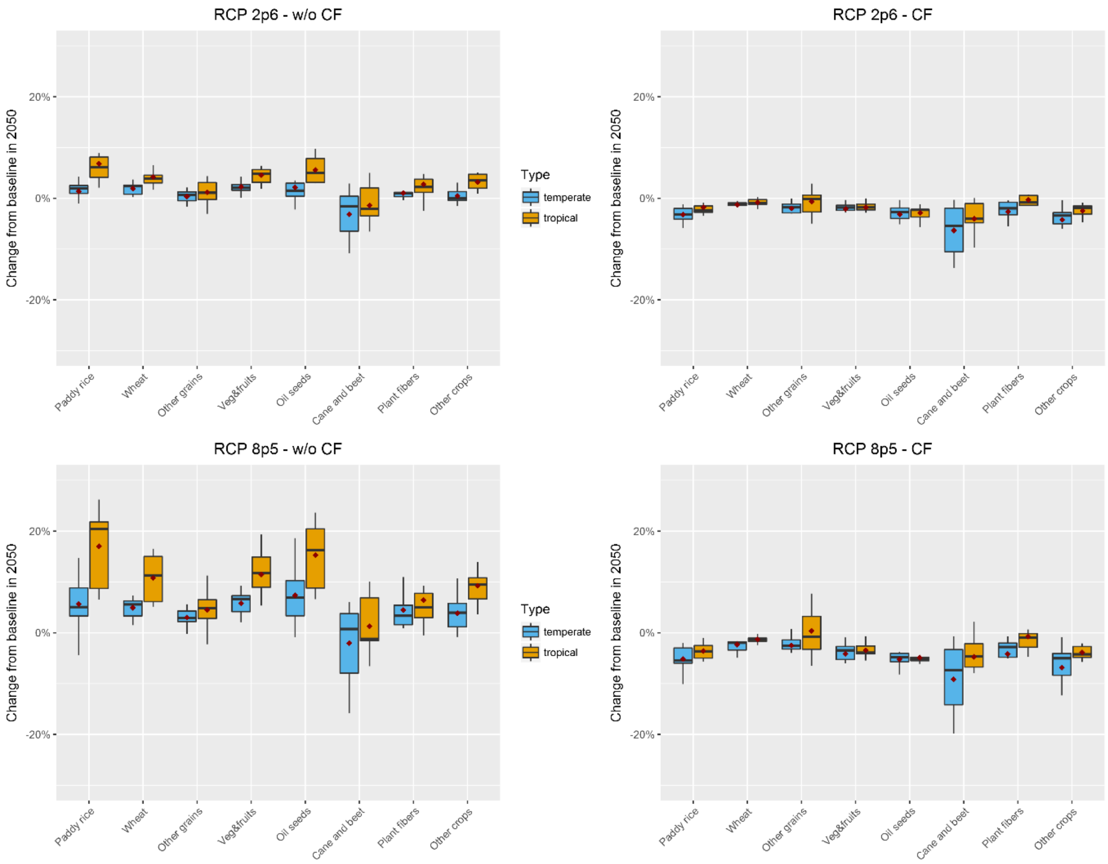


Figure B1 – Crop prices changes across RCPs and CF variants in 2050 relative to the baseline

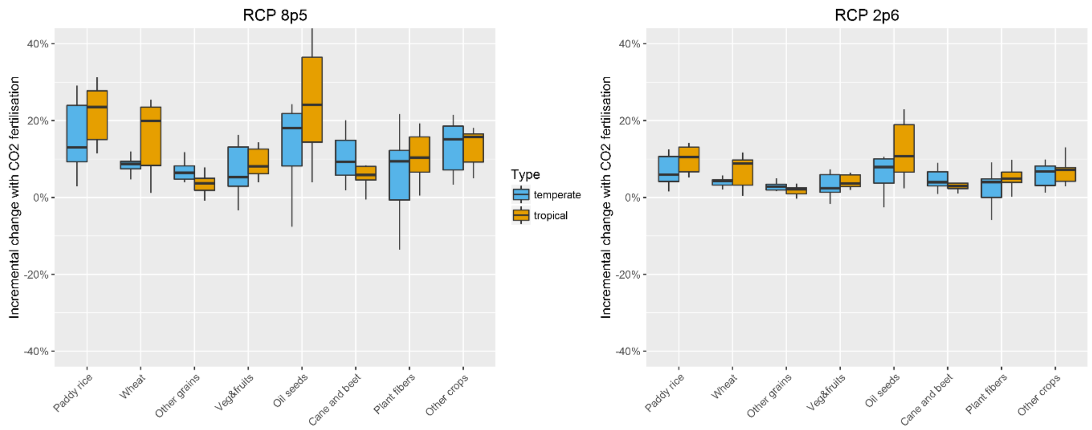


Figure B2 – Incremental output changes of CF in 2050 relative to the baseline

Note: The changes are calculated as the difference between output between the two CF variants in each RCP

Table B1 Changes in regional water requirements (in km^3) by crop type and by CF variant in 2050 relative to the baseline - RCP 2.6

Region	Overall		Wheat		Rice		Other grains		Veg&fruits		Fiber plants		Cane&beet		Oil seeds		Other crops	
	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF	CF	w/o CF
Australia&NZ	0.0	0.3	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.0)	0.4	0.5	0.1	0.0	0.0	0.0	(0.1)	0.0
Brazil	(0.7)	0.0	(0.0)	0.0	(0.2)	(0.1)	(0.0)	(0.0)	(0.2)	0.2	0.0	0.0	(0.1)	(0.2)	(0.0)	0.0	(0.1)	0.0
Sahel	(0.9)	0.1	(0.0)	(0.0)	(0.2)	0.6	(0.0)	(0.0)	(0.1)	(0.2)	0.0	0.0	(0.2)	(0.2)	0.0	0.0	(0.3)	(0.0)
Central Africa	(1.9)	1.4	(0.0)	(0.0)	(0.7)	1.4	0.4	0.4	(0.6)	(0.0)	(0.0)	(0.0)	(0.1)	(0.2)	0.0	0.0	(0.8)	(0.2)
Central Asia	(2.9)	0.4	(4.7)	(2.7)	(0.0)	(0.1)	(1.7)	(1.0)	(1.5)	(0.9)	5.1	5.2	(0.0)	(0.0)	(0.0)	0.0	(0.0)	(0.2)
China	33.4	43.2	(0.6)	1.2	21.8	21.4	6.6	9.0	1.9	5.7	1.5	2.0	(0.9)	(0.8)	3.0	4.6	0.1	0.1
Eurasia	(2.0)	(0.9)	(1.4)	(1.0)	(0.1)	(0.2)	(0.1)	0.2	0.0	0.3	0.0	0.3	0.0	0.1	(0.1)	(0.0)	(0.5)	(0.5)
India	(58.7)	(46.2)	(31.8)	(25.9)	8.8	6.0	(0.7)	(0.7)	(4.4)	1.6	(10.0)	(8.6)	(10.0)	(10.9)	(2.4)	(1.2)	(8.2)	(6.4)
Middle East	(15.2)	(4.7)	(6.1)	(5.8)	(0.3)	(0.3)	(0.0)	0.2	(7.2)	1.3	4.2	5.4	(0.5)	(0.7)	(0.8)	(0.6)	(4.6)	(4.2)
Northern Africa	(14.1)	(6.3)	(1.4)	(2.0)	(1.4)	(1.2)	(4.5)	(4.2)	(3.4)	(0.5)	3.2	3.5	(1.6)	(1.6)	(0.2)	(0.1)	(4.8)	(0.2)
Northeast Asia	1.0	1.6	(0.0)	0.0	0.8	1.3	0.0	0.0	(0.0)	0.0	0.0	0.0	(0.0)	0.0	0.2	0.2	0.1	0.1
Northern Europe	(0.0)	0.1	(0.0)	(0.0)	0.0	0.0	(0.0)	0.0	0.0	0.1	0.0	0.0	(0.0)	0.0	0.0	0.0	(0.0)	0.0
North Latin Am	(1.9)	(0.9)	(0.8)	(2.2)	0.3	(0.6)	1.0	1.2	(2.3)	(0.1)	0.6	0.6	(0.7)	(1.1)	(0.2)	1.2	0.3	0.2
Canada	(0.2)	(0.2)	(0.0)	(0.1)	0.0	0.0	0.0	(0.0)	(0.0)	0.0	0.0	0.0	0.0	0.0	(0.1)	(0.1)	(0.0)	(0.1)
Southern Africa	(0.3)	0.1	(0.1)	(0.2)	0.0	0.0	0.3	0.5	0.1	0.3	(0.0)	0.0	(0.3)	(0.3)	0.0	0.0	(0.2)	(0.2)
South Asia	(22.7)	(16.7)	(7.9)	(8.1)	(1.5)	(1.1)	(1.0)	(0.4)	(4.9)	(1.8)	(2.3)	(2.0)	(2.8)	(2.3)	(0.1)	0.0	(2.1)	(1.1)
Southeast Asia	(7.4)	(0.6)	(2.2)	(1.2)	(5.4)	(4.2)	0.0	0.0	1.7	4.3	(0.0)	0.0	(1.1)	(0.4)	(0.0)	0.0	(0.4)	0.8
Southern Europe	0.5	4.8	(0.3)	(0.2)	(0.1)	(0.1)	1.1	1.4	(1.5)	1.3	1.6	1.8	0.0	0.1	(0.2)	0.0	(0.3)	0.6
South Latin Am	(0.4)	0.7	(0.1)	(0.1)	(0.1)	(0.2)	0.2	0.4	(0.2)	(0.1)	0.1	0.0	(0.5)	(0.5)	0.2	1.1	0.0	(0.1)
USA	(10.8)	(4.8)	(2.3)	(2.1)	(0.8)	(0.2)	(2.3)	(2.4)	(1.2)	0.3	0.7	1.9	(0.1)	(0.1)	(4.4)	(1.8)	(0.4)	(0.4)
World	(105.1)	(28.4)	(59.8)	(50.4)	20.6	22.5	(1.0)	4.7	(24.0)	11.9	5.2	10.6	(18.8)	(19.1)	(5.0)	3.4	(22.4)	(11.9)

Table B2 Changes in regional crop production by crop type and by growing method in 2050 relative to the baseline - RCP 2.6 CF

Region	Wheat		Rice		Other grains		Veg&fruits		Fiber plants		Cane&beet		Oil seeds		Other crops	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
Australia&NZ	1%	1%	5%	24%	-3%	10%	-2%	0%	14%	13%	29%	-7%	-28%	3%	2%	12%
Brazil	-2%	0%	3%	0%	-6%	3%	-4%	1%	10%	3%	2%	8%	-2%	0%	-3%	5%
Sahel	-7%	1%	-9%	0%	8%	2%	-11%	-8%	44%	52%	-19%	6%	-15%	2%	-12%	2%
Central Africa	6%	-2%	6%	-1%	99%	-1%	-2%	-1%	-25%	6%	-45%	30%	12%	1%	-4%	5%
Central Asia	-17%	18%	8%	53%	-3%	29%	-8%	37%	22%	21%	9%	263%	12%	28%	10%	96%
China	5%	9%	9%	1%	10%	-7%	3%	4%	46%	12%	-6%	51%	23%	8%	22%	7%
Eurasia	-4%	3%	-4%	23%	-2%	5%	5%	1%	7%	25%	6%	3%	-14%	7%	-6%	7%
India	4%	-7%	16%	-35%	-9%	-2%	-3%	24%	-56%	81%	-9%	110%	-41%	18%	-16%	14%
Middle East	-2%	-1%	6%	45%	3%	1%	-2%	0%	23%	30%	-1%	-4%	-11%	21%	-3%	17%
Northern Africa	-3%	5%	10%	0%	27%	8%	-3%	4%	13%	-5%	7%	2%	-2%	5%	10%	4%
Northeast Asia	5%	0%	2%	31%	-9%	13%	-10%	-5%	-1%	14%	5%	-1%	63%	2%	27%	-3%
Northern Europe	-4%	-1%	8%	-61%	-30%	26%	-1%	3%	-9%	70%	13%	-40%	-2%	19%	-3%	-2%
North Latin Am	-18%	4%	21%	7%	-2%	7%	-2%	2%	13%	83%	0%	7%	-29%	18%	1%	6%
Canada	1%	18%	4%	5%	-5%	1%	3%	-1%	15%	9%	-13%	29%	0%	8%	-7%	2%
Southern Africa	4%	7%	7%	2%	2%	-9%	-4%	5%	-8%	71%	-7%	541%	0%	10%	-3%	60%
South Asia	-4%	4%	3%	45%	21%	-2%	1%	0%	12%	3%	16%	67%	13%	-4%	14%	8%
Southeast Asia	-8%	6%	1%	9%	0%	-6%	12%	-5%	-4%	7%	-14%	23%	-9%	10%	-3%	9%
Southern Europe	-3%	-4%	14%	6%	42%	-1%	4%	38%	-6%	59%	24%	6%	29%	9%	1%	11%
South Latin Am	1%	-2%	1%	-3%	5%	-2%	-2%	-2%	26%	21%	0%	-1%	-2%	1%	1%	-2%
USA	-6%	3%	4%	26%	-6%	2%	-1%	6%	8%	12%	3%	18%	-8%	3%	0%	12%
World	**1%**	**1%**	**7%**	**4%**	**5%**	**1%**	**0%**	**2%**	**6%**	**21%**	**0%**	**15%**	**3%**	**5%**	**0%**	**5%**

Table B3 Changes in regional crop production by crop type and by growing method in 2050 relative to the baseline - RCP 2.6 without CF

Region	Wheat		Rice		Other grains		Veg&fruits		Fiber plants		Cane&beet		Oil seeds		Other crops	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
Australia&NZ	-9%	-3%	-4%	-9%	-3%	4%	-5%	-4%	10%	7%	25%	-17%	4%	-5%	6%	-4%
Brazil	-5%	-3%	-3%	-7%	-7%	1%	-1%	-4%	8%	-1%	-3%	5%	3%	-11%	-1%	-3%
Sahel	-12%	-4%	-15%	-1%	4%	-1%	-1%	-11%	44%	56%	-14%	-4%	-23%	-7%	-15%	-4%
Central Africa	-36%	-11%	13%	-15%	86%	-3%	-5%	-7%	-25%	-1%	-50%	24%	42%	-10%	-4%	-5%
Central Asia	-11%	5%	-4%	7%	-2%	5%	-11%	18%	8%	15%	4%	46%	2%	-3%	-6%	14%
China	2%	5%	-4%	-2%	11%	-10%	1%	-8%	41%	-8%	-6%	48%	20%	-12%	7%	-1%
Eurasia	-9%	-1%	-18%	26%	1%	2%	3%	-4%	16%	13%	-2%	-1%	-10%	-1%	-15%	4%
India	-6%	-9%	3%	-51%	-11%	-2%	0%	-6%	-50%	63%	-14%	130%	-25%	-4%	-18%	5%
Middle East	-10%	1%	-1%	71%	3%	-8%	1%	-14%	19%	33%	-10%	-6%	-12%	10%	-8%	-7%
Northern Africa	-19%	-1%	-9%	-5%	25%	7%	-3%	-10%	11%	2%	1%	2%	61%	-24%	3%	-5%
Northeast Asia	8%	7%	0%	-2%	1%	10%	-6%	-7%	3%	11%	5%	-3%	39%	9%	16%	-4%
Northern Europe	-14%	0%	2%	-92%	-29%	22%	-3%	-5%	-14%	40%	11%	-40%	-1%	2%	0%	-19%
North Latin Am	-16%	1%	41%	16%	2%	5%	2%	3%	9%	53%	0%	3%	-26%	20%	4%	4%
Canada	-24%	-8%	13%	-29%	-3%	-1%	-13%	-4%	34%	1%	-17%	26%	4%	-36%	-1%	-18%
Southern Africa	-7%	-14%	-4%	-35%	1%	-8%	-4%	-3%	-12%	33%	-8%	441%	1%	-8%	-6%	30%
South Asia	-9%	-2%	-9%	39%	28%	-9%	-4%	-9%	0%	4%	14%	58%	43%	-18%	1%	3%
Southeast Asia	-14%	-6%	-10%	-8%	-8%	-5%	5%	-10%	3%	2%	-14%	20%	-19%	-13%	-4%	-10%
Southern Europe	-19%	-4%	3%	3%	53%	-5%	2%	23%	-11%	48%	18%	4%	32%	-5%	-3%	1%
South Latin Am	-4%	-4%	-3%	-4%	5%	-6%	0%	-6%	22%	-22%	-3%	-5%	-5%	-1%	3%	-9%
USA	-10%	-1%	-1%	17%	-7%	-4%	-2%	-4%	4%	5%	-1%	8%	-6%	-7%	-5%	2%
World	**-7%**	**-1%**	**-2%**	**-10%**	**6%**	**-2%**	**-1%**	**-7%**	**3%**	**8%**	**-4%**	**11%**	**4%**	**-8%**	**-1%**	**-2%**

Table B4 Changes in regional crop production by crop type and by growing method in 2050 relative to the baseline - RCP 8.5 CF

Region	Wheat		Rice		Other grains		Veg&fruits		Fiber plants		Cane&beet		Oil seeds		Other crops	
	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed
Australia&NZ	3%	4%	7%	24%	-1%	10%	-1%	2%	16%	12%	43%	-6%	-23%	7%	9%	16%
Brazil	-2%	-2%	3%	1%	-8%	2%	-4%	2%	16%	3%	-1%	12%	1%	2%	-4%	7%
Sahel	-15%	6%	-4%	5%	17%	3%	-16%	1%	45%	53%	-23%	12%	-11%	5%	-13%	8%
Central Africa	14%	-5%	3%	2%	124%	-2%	1%	0%	-43%	11%	-52%	47%	-1%	5%	-12%	10%
Central Asia	-13%	16%	10%	162%	-6%	45%	-12%	70%	43%	-12%	12%	521%	29%	25%	21%	180%
China	-1%	27%	17%	-4%	8%	-9%	3%	12%	59%	28%	-11%	67%	29%	19%	29%	15%
Eurasia	-3%	4%	-2%	27%	-5%	5%	7%	2%	3%	24%	9%	3%	-19%	12%	-4%	10%
India	6%	-33%	23%	-54%	3%	-7%	5%	18%	-61%	83%	-43%	418%	-14%	12%	-15%	12%
Middle East	5%	-4%	10%	51%	-1%	16%	-6%	16%	26%	32%	6%	-10%	-8%	41%	0%	53%
Northern Africa	3%	3%	21%	6%	23%	14%	-2%	8%	14%	-4%	12%	3%	-1%	12%	14%	8%
Northeast Asia	4%	-2%	5%	46%	-11%	21%	-12%	-2%	0%	21%	6%	0%	93%	4%	36%	-2%
Northern Europe	1%	-4%	10%	-34%	-51%	48%	0%	1%	-13%	73%	16%	-46%	-3%	28%	-8%	16%
North Latin Am	-19%	5%	31%	7%	-1%	7%	-2%	1%	14%	100%	3%	7%	-32%	21%	4%	7%
Canada	11%	22%	1%	16%	-13%	0%	18%	0%	-12%	13%	-24%	47%	-4%	38%	-16%	8%
Southern Africa	5%	-20%	10%	-31%	-1%	-23%	-3%	6%	-7%	42%	-27%	1661%	9%	12%	-7%	63%
South Asia	-7%	11%	10%	76%	32%	-7%	2%	9%	27%	0%	25%	113%	-11%	7%	27%	19%
Southeast Asia	-9%	2%	5%	14%	0%	-14%	24%	-6%	-15%	7%	-32%	48%	-12%	16%	-2%	11%
Southern Europe	9%	-9%	21%	1%	82%	-3%	2%	91%	-2%	62%	39%	11%	51%	9%	2%	22%
South Latin Am	2%	-3%	3%	-3%	6%	-2%	-3%	-1%	29%	32%	4%	-2%	-1%	2%	0%	0%
USA	-12%	9%	5%	5%	-11%	2%	-2%	18%	13%	4%	3%	26%	-11%	8%	2%	15%
World	**2%**	**2%**	**12%**	**7%**	**4%**	**1%**	**0%**	**6%**	**8%**	**27%**	**-8%**	**27%**	**5%**	**9%**	**1%**	**7%**

Annex C: Chapter 8 - Global economic impacts of regional water scarcity under different climate scenarios

Table C1 - Water productivity - India (real $ output/m3)

Sector	baseline	LM	AL	FA	MF
Livestock	237.968	236.220	237.848	237.465	236.255
Electricity - thermal	20.149	20.761	20.144	20.215	20.409
Veg&fruits (I)	2.500	2.579	2.344	2.360	2.362
Other crops (I)	0.892	0.929	0.847	0.851	0.851
Oil seeds (I)	0.724	0.753	0.730	0.725	0.721
Fiber plants (I)	0.694	0.727	0.725	0.716	0.710
Municipal water	0.427	0.646	0.428	0.505	0.777
Other grains (I)	0.489	0.510	0.563	0.548	0.539
Cane&beet (I)	0.379	0.427	0.409	0.402	0.398
Rice (I)	0.255	0.287	0.307	0.296	0.290
Wheat (I)	0.219	0.248	0.269	0.259	0.254
Industrial water	0.038	0.427	0.039	0.119	0.414

Table C2 - Water productivity – South Asia (real $ output/m3)

Sector	baseline	LM	AL	FA	MF
Livestock	52.817	51.838	52.704	52.681	52.599
Electricity - thermal	3.964	4.475	3.963	4.014	4.126
Oil seeds (I)	2.034	1.944	1.480	1.498	1.521
Municipal water	0.291	0.375	0.291	0.340	0.450
Industrial water	0.091	1.266	0.091	0.140	0.251
Veg&fruits (I)	0.343	0.377	0.305	0.306	0.306
Fiber plants (I)	0.188	0.222	0.199	0.198	0.196
Cane&beet (I)	0.164	0.196	0.172	0.171	0.169
Rice (I)	0.110	0.136	0.133	0.132	0.130
Wheat (I)	0.081	0.093	0.108	0.106	0.104
Other crops (I)	0.080	0.093	0.107	0.105	0.103
Other grains (I)	0.071	0.081	0.110	0.108	0.105

Table C3 - Water productivity – Middle East (real $ output/m3)

Sector	baseline	LM	AL	FA	MF
Livestock	42.011	41.797	42.172	41.871	41.560
Electricity - thermal	4.495	4.957	4.488	4.601	4.720
Oil seeds (I)	0.771	0.896	0.884	0.759	0.743
Other grains (I)	0.575	0.685	1.006	0.702	0.623
Veg&fruits (I)	0.646	0.756	0.753	0.637	0.622
Fiber plants (I)	0.427	0.543	0.929	0.600	0.508
Wheat (I)	0.292	0.337	0.825	0.472	0.378
Cane&beet (I)	0.290	0.343	0.707	0.419	0.346
Municipal water	0.268	0.466	0.268	0.394	0.526
Industrial water	0.132	0.949	0.132	0.260	0.393
Rice (I)	0.196	0.253	0.598	0.320	0.251
Other crops (I)	0.094	0.109	0.559	0.240	0.165

Table C4 - Water productivity – Northern Africa (real $ output/m^3)

Sector	baseline	LM	AL	FA	MF
Electricity - thermal	5480.521	5477.897	5479.503	5480.431	5479.748
Livestock	18.327	18.373	18.336	18.332	18.342
Oil seeds (I)	2.475	2.374	2.442	2.438	2.439
Veg&fruits (I)	1.119	1.151	1.112	1.110	1.110
Municipal water	0.651	0.702	0.650	0.654	0.724
Fiber plants (I)	0.619	0.654	0.619	0.618	0.618
Industrial water	0.475	0.552	0.475	0.479	0.547
Wheat (I)	0.288	0.298	0.292	0.291	0.291
Rice (I)	0.242	0.259	0.244	0.243	0.243
Cane&beet (I)	0.218	0.237	0.222	0.221	0.221
Other grains (I)	0.130	0.134	0.134	0.133	0.133
Other crops (I)	0.041	0.043	0.046	0.046	0.046

Table C5 - Sectoral share in regional value-added - 2050 baseline values

Region	Crops	Processed food	Agri non-crops	Industry and services
Australia&NZ	0.7%	2.0%	0.8%	96.5%
Brazil	2.3%	1.9%	1.0%	94.8%
Sahel	5.2%	3.7%	3.2%	87.9%
Central Africa	6.2%	5.9%	3.0%	85.0%
Central Asia	1.5%	2.4%	0.6%	95.5%
China	1.4%	0.8%	1.3%	96.5%
Eurasia	1.8%	1.7%	1.2%	95.3%
India	1.3%	1.6%	1.6%	95.5%
Middle East	1.5%	1.7%	0.6%	96.2%
Northern Africa	3.9%	2.7%	1.3%	92.1%
Northeast Asia	0.8%	1.8%	0.4%	97.0%
Northern Europe	0.4%	2.2%	0.6%	96.9%
North Latin Am	1.4%	3.4%	0.9%	94.4%
Canada	0.6%	2.2%	0.8%	96.4%
Southern Africa	1.2%	2.3%	1.0%	95.5%
South Asia	2.9%	13.6%	1.1%	82.3%
Southeast Asia	1.8%	2.4%	2.5%	93.4%
Southern Europe	1.2%	2.5%	0.6%	95.8%
South Latin Am	1.9%	2.9%	0.9%	94.3%
USA	0.6%	1.6%	0.2%	97.5%

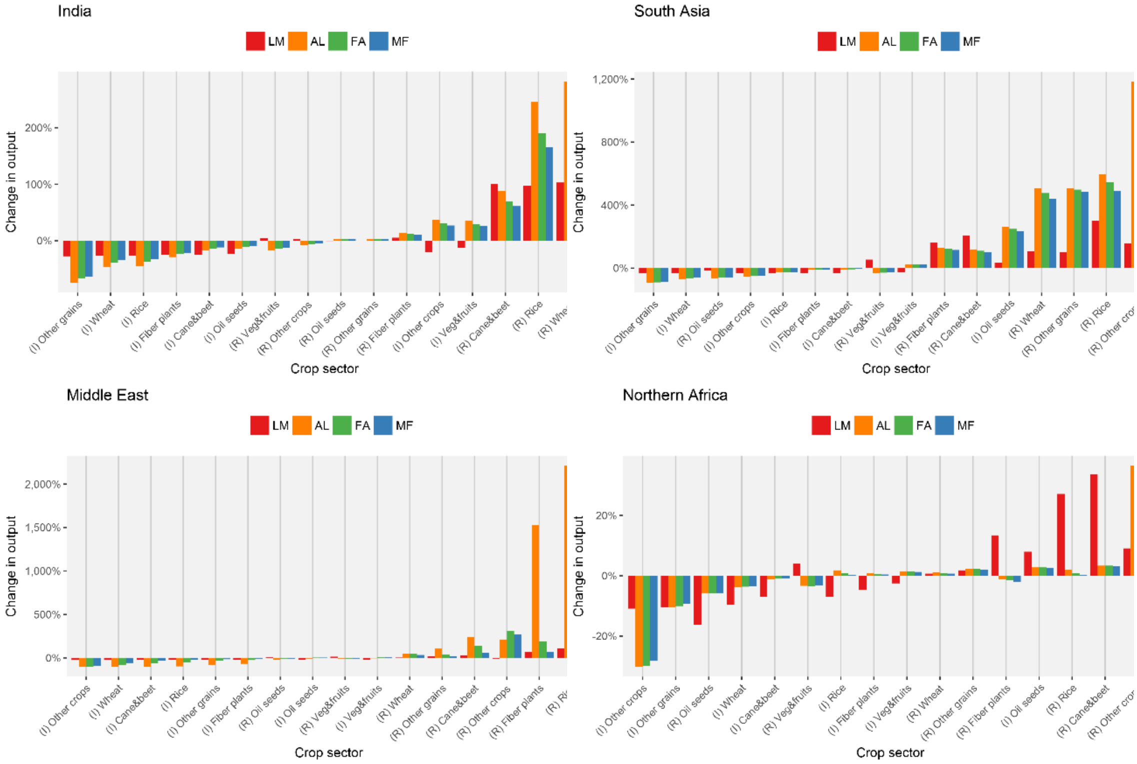


Figure C1 - Crop production impacts by growing method – in 2050

Note: *(I) – irrigated, (R) - rainfed*

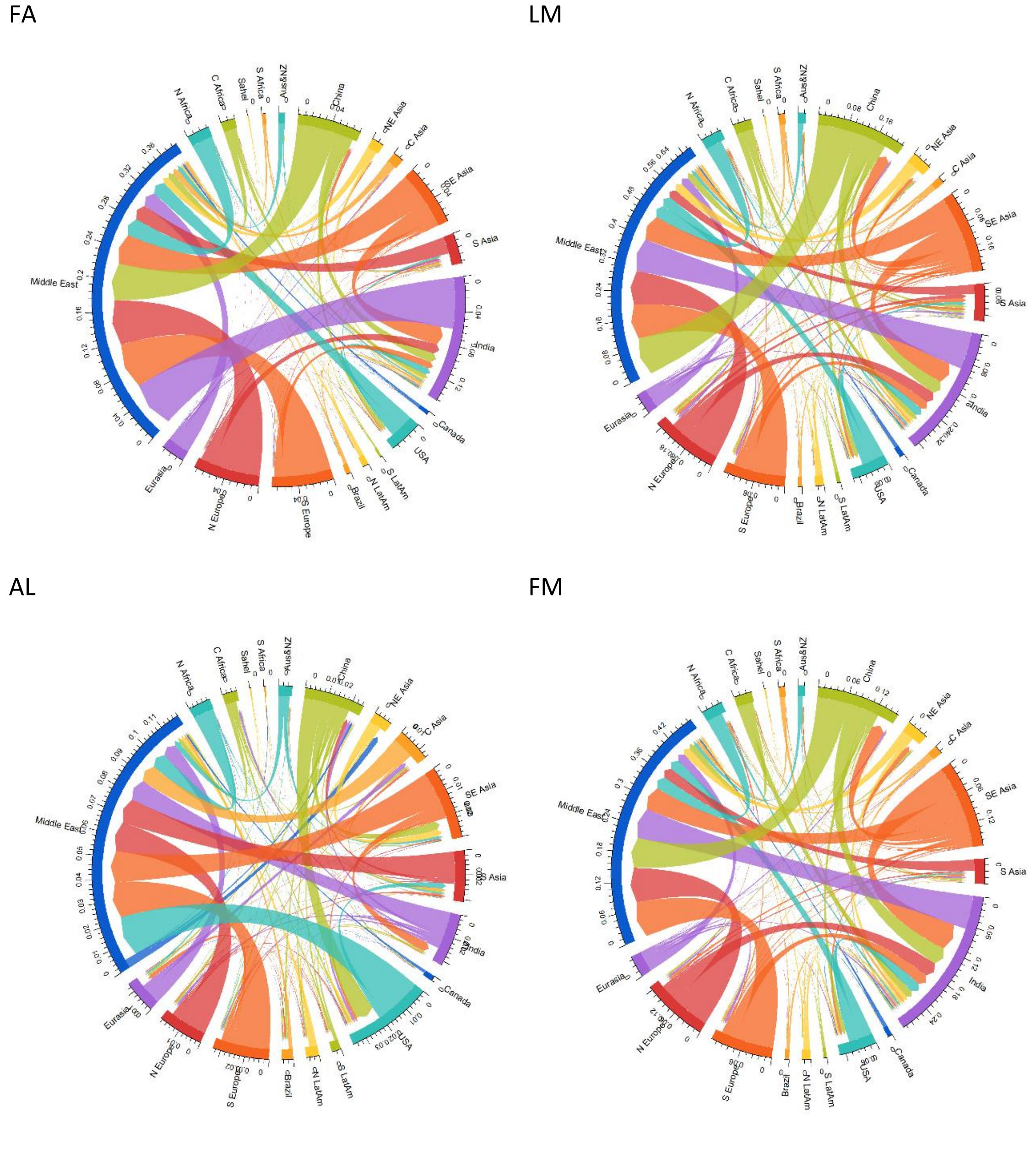


Figure C2 – Virtual water trade of industrial water by allocation method – changes in 2050

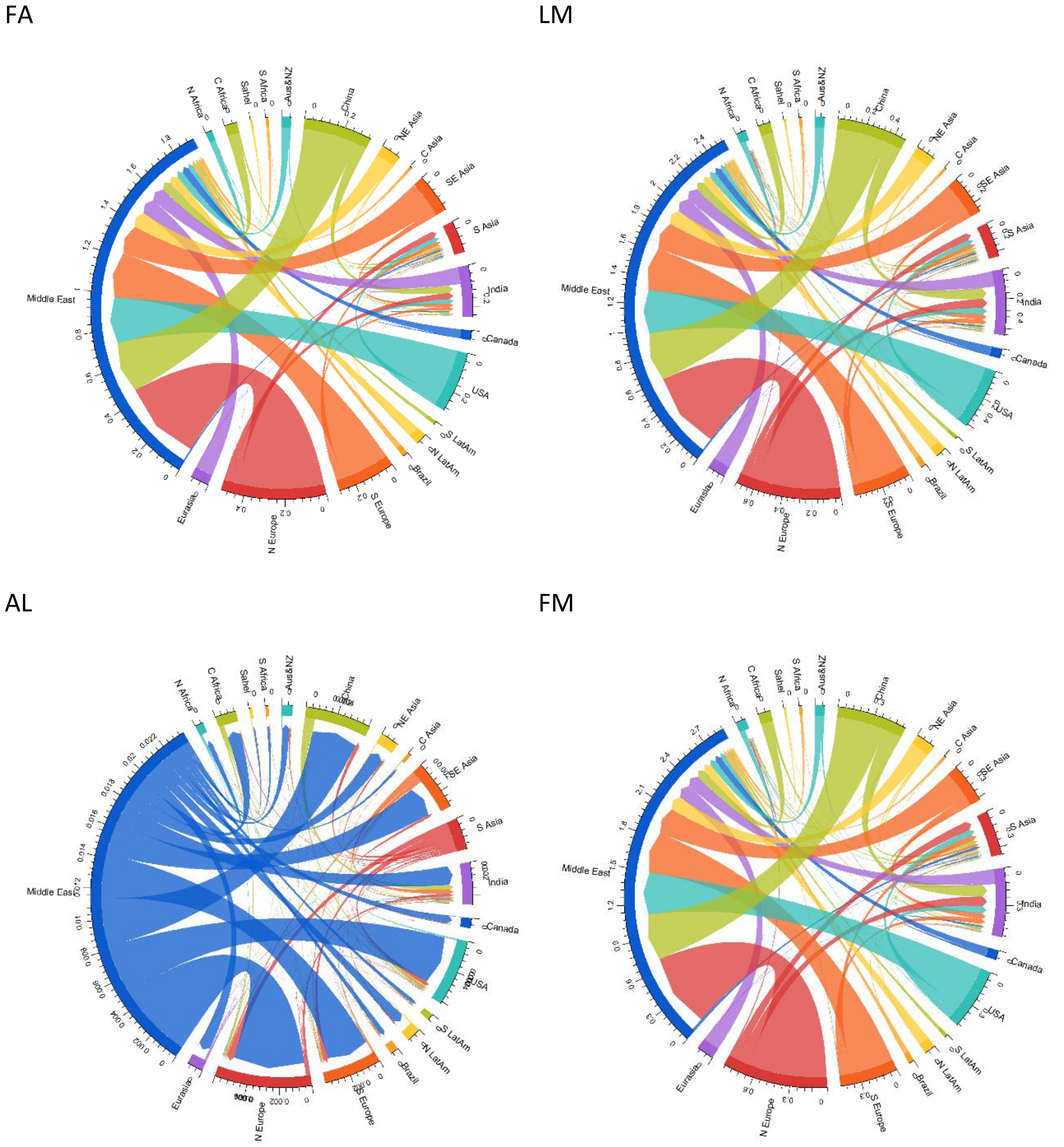
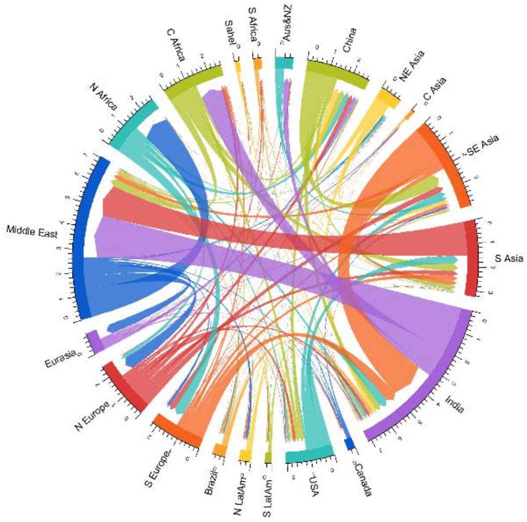
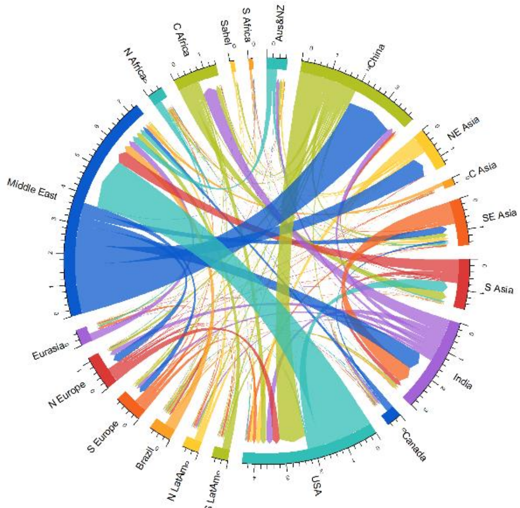


Figure C3 – Virtual water trade of municipal water by allocation method – changes in 2050

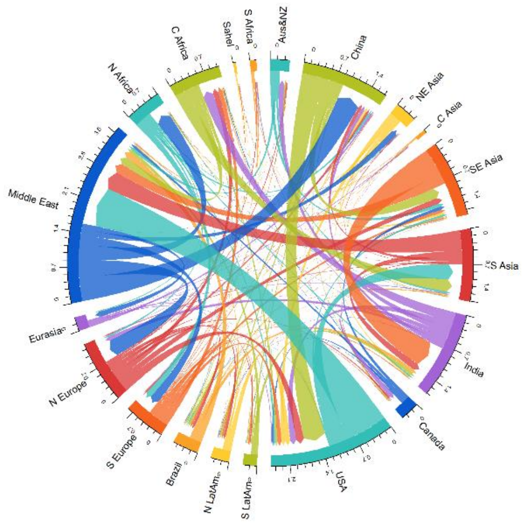
LM



AL



FA



MF

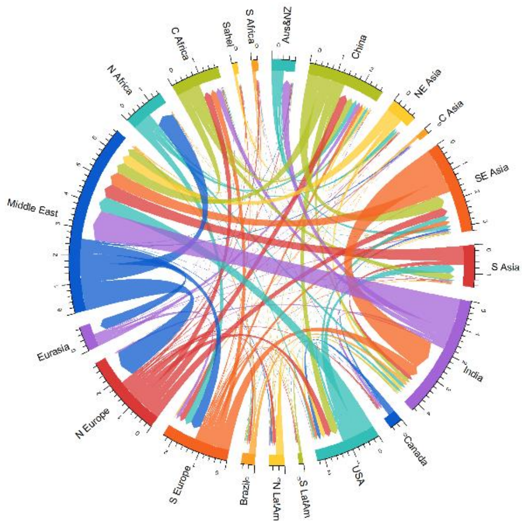


Figure C4 – Changes in net trade in 2050 – values at constant prices

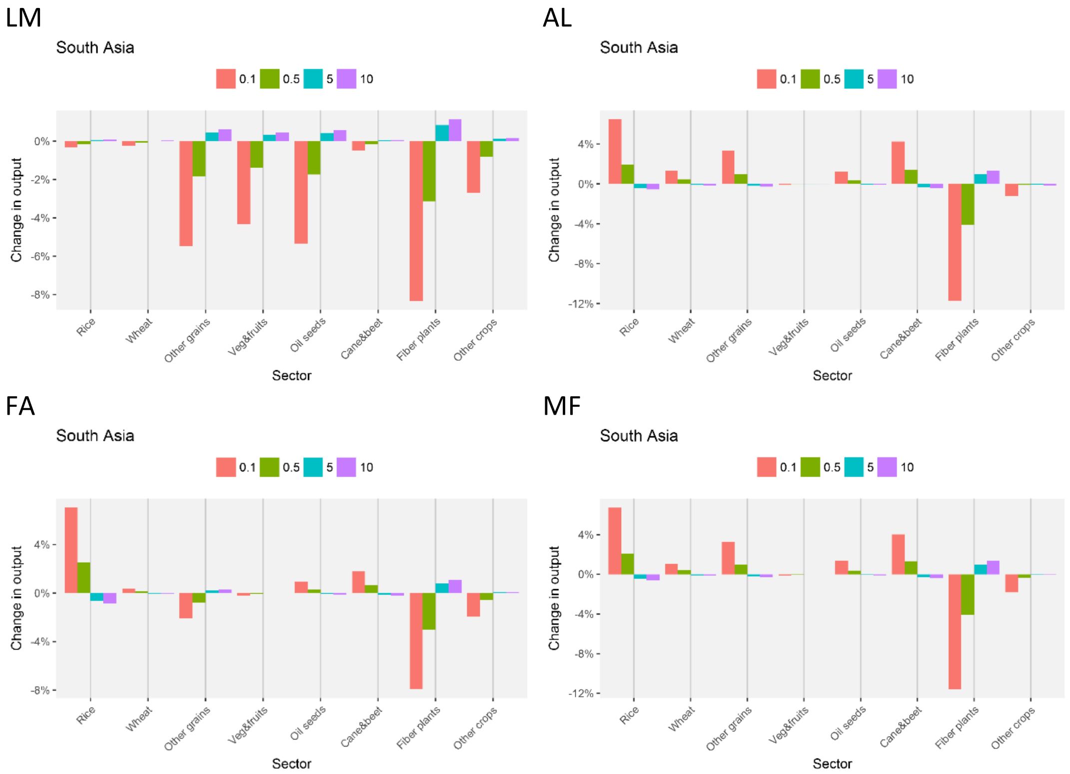


Figure C5 – Crop output deviations in 2050 in South Asia from base parametrisation - σ_{AL} sensitivity

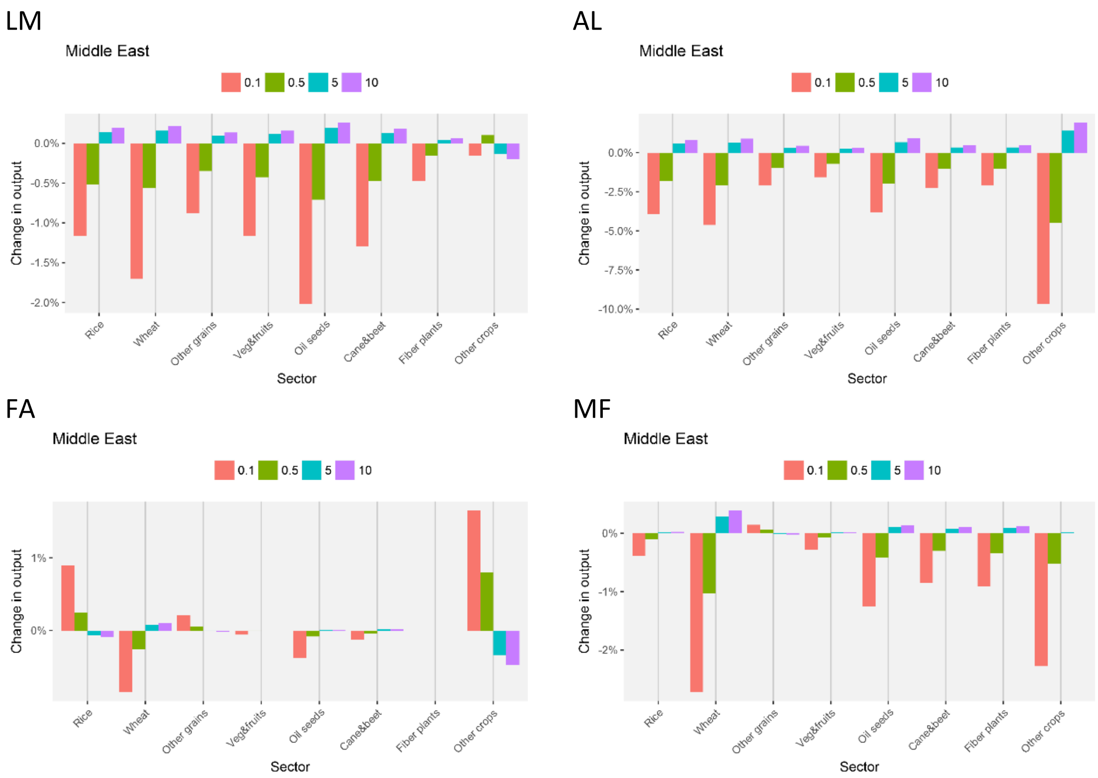


Figure C6 – Sectoral output deviations in 2050 in the Middle East from base parametrisation - σ_{AL} sensitivity

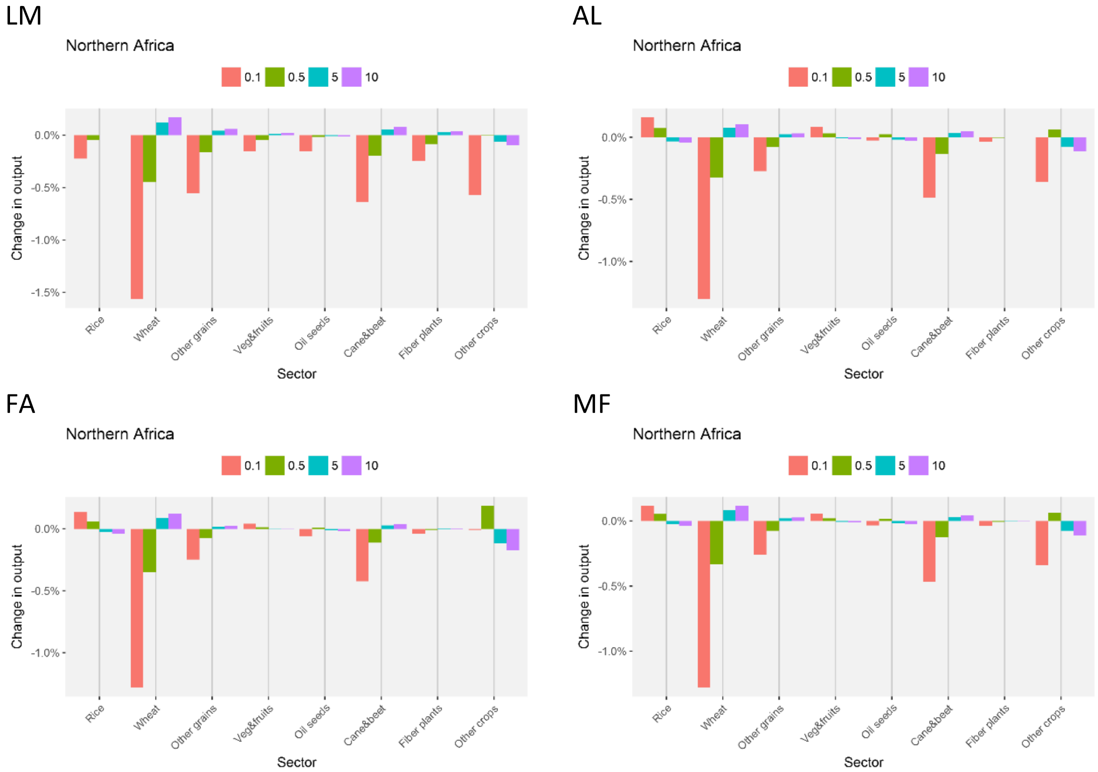


Figure C7 – Sectoral output deviations in 2050 in Northern Africa from base parametrisation - σ_{AL} sensitivity

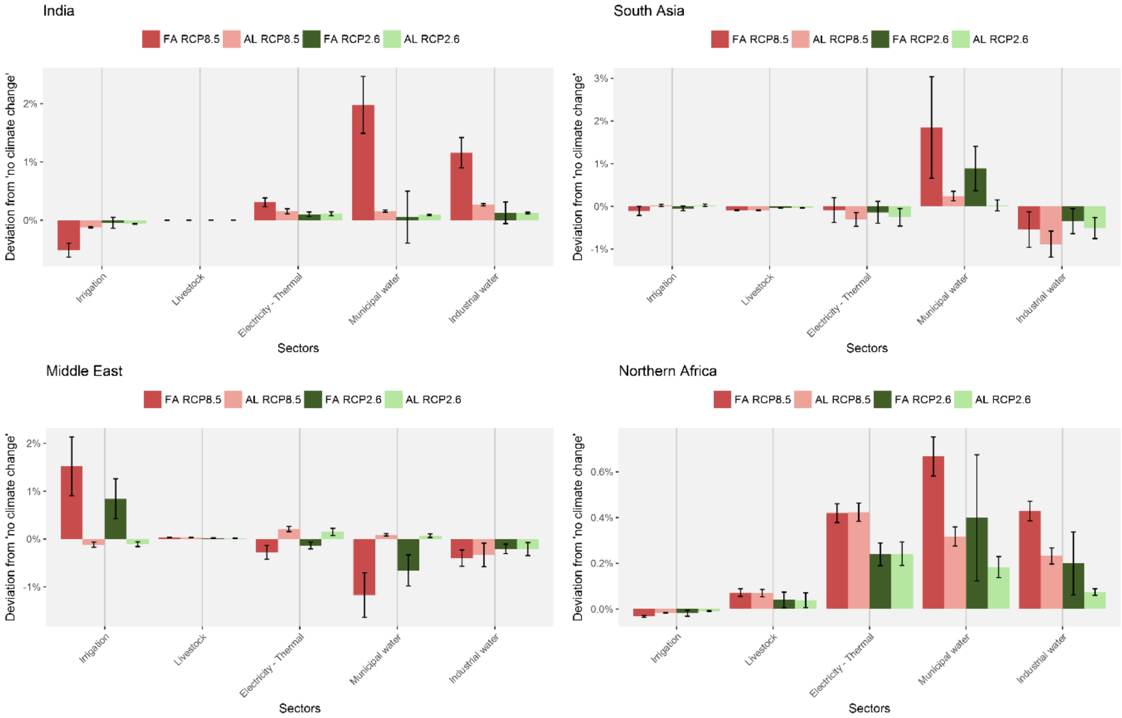


Figure C8 – Climate change: changes in withdrawals in 2050 from no climate change scenario (%)

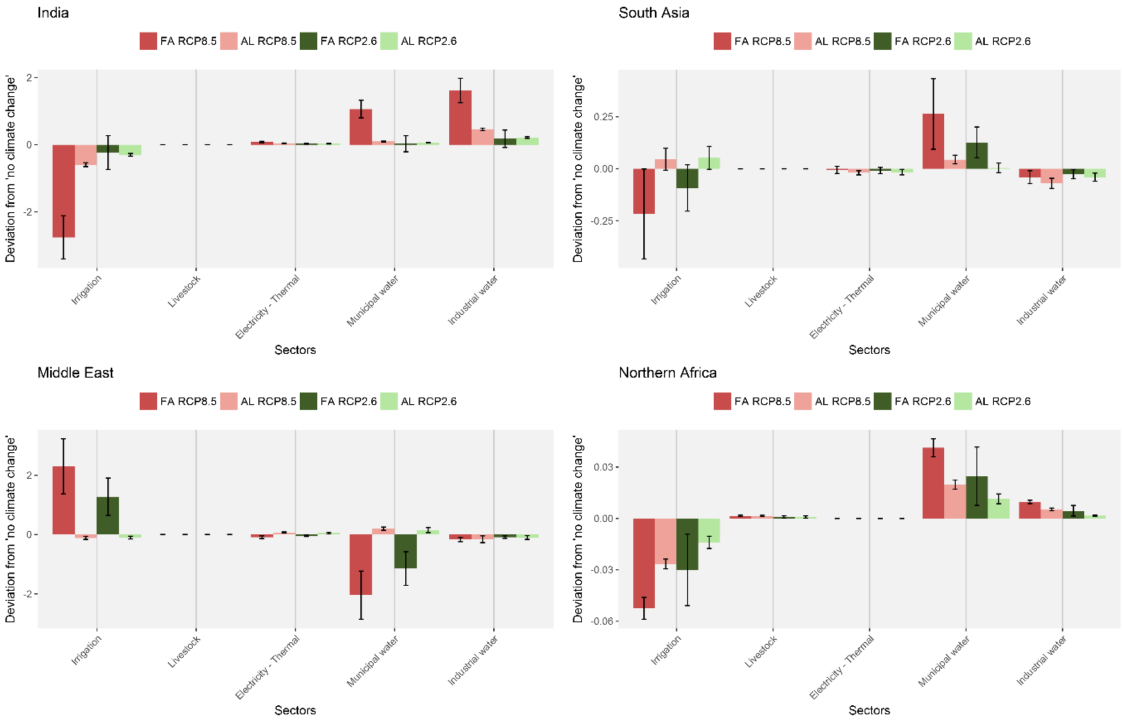


Figure C9 - Climate change: changes in withdrawals in 2050 from the no climate change scenario (volumes in km3)

Sensitivity analysis of σ_{ND2} (water-intensive industrial sector dependency on water inputs)

This sensitivity analysis is testing the robustness of the model results in relation to the elasticity of substitution σ_{ND2} between industrial water inputs and the composite of all other intermediate inputs ND2 (see Figure 4.6 in Chapter 4). This is done by increasing the value of σ_{ND2} from the initial level of 0.01 (close to perfect complements) to a level of 2 for the LM allocation method (the variant with the highest GDP impacts of water scarcity).

The negative impacts over real GDP are considerably reduced across all regions. In India these even become positive for an elasticity value of over 0.5 marking the re-allocation of non-water resources to non-crop sectors boosting their output (Figure C6). For South Asia and the Middle East however, the impacts are still non-negligible even for the highest elasticity value.

The reduction in impacts with an increased elasticity value is observed across all sectors (Figure C6), but notably for the water-intensive sectors using industrial water as an input (primary energy, chemicals, manufacturing, mining and paper). The substitution effect is felt also for thermal power generation as more water is diverted from the industrial water sector to the other self-supplied sectors – this is in spite of self-abstracting sectors having a zero-elasticity of substitution of water as a factor of production.

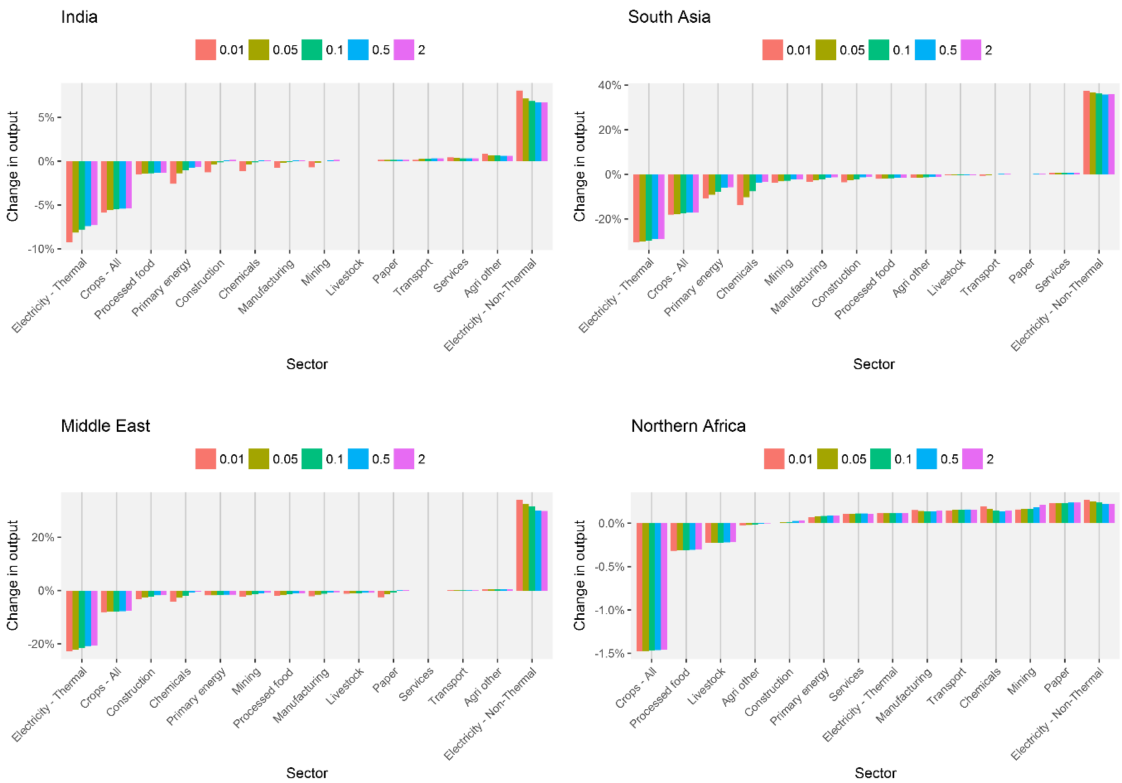


Figure C10 - Sectoral output impacts in water scarce regions by sigmaND2 value - Limited Mobility (LM) allocation method

Table C6 – Real GDP impacts in RESCU-Water regions by sigmaND2 value - Limited Mobility (LM) allocation method (values in percentage points)

Region	0.01	0.05	0.1	0.5	2
Middle East	-1.797	-1.599	-1.480	-1.292	-1.232
South Asia	-1.606	-1.332	-1.131	-0.835	-0.770
India	-0.435	-0.148	-0.057	0.042	0.071
Northern Africa	-0.022	-0.017	-0.014	-0.009	-0.006
Central Asia	-0.016	-0.013	-0.012	-0.009	-0.009
Eurasia	-0.009	-0.007	-0.005	-0.003	-0.003
China	-0.002	-0.002	-0.002	-0.001	0.002
Northern Europe	-0.002	-0.001	-0.001	-0.000	-0.000
Southern Europe	-0.001	-0.000	-0.000	0.000	-0.000
Northeast Asia	-0.000	-0.000	-0.000	-0.000	-0.001
North Latin Am	-0.001	-0.000	-0.000	0.000	0.000
USA	0.000	0.000	0.000	0.001	0.000
Southeast Asia	-0.002	0.001	0.002	0.003	0.001
Canada	0.000	0.001	0.001	0.001	0.001
Central Africa	-0.006	-0.000	0.002	0.006	0.007
Australia&NZ	0.001	0.002	0.003	0.004	0.003
Brazil	0.002	0.002	0.002	0.003	0.003
Sahel	0.001	0.004	0.005	0.006	0.004
Southern Africa	0.001	0.004	0.005	0.006	0.005
South Latin Am	0.005	0.006	0.006	0.006	0.005
World	**-0.146**	**-0.109**	**-0.093**	**-0.072**	**-0.066**